Neutrino Astronomy – Status and Perspectives

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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HEAP'09
KEK, 11. November 2009

Friedrich-Alexander-Universität Erlangen-Nürnberg

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Outline

Introduction to neutrino astronomy

Currently operating neutrino telescopes

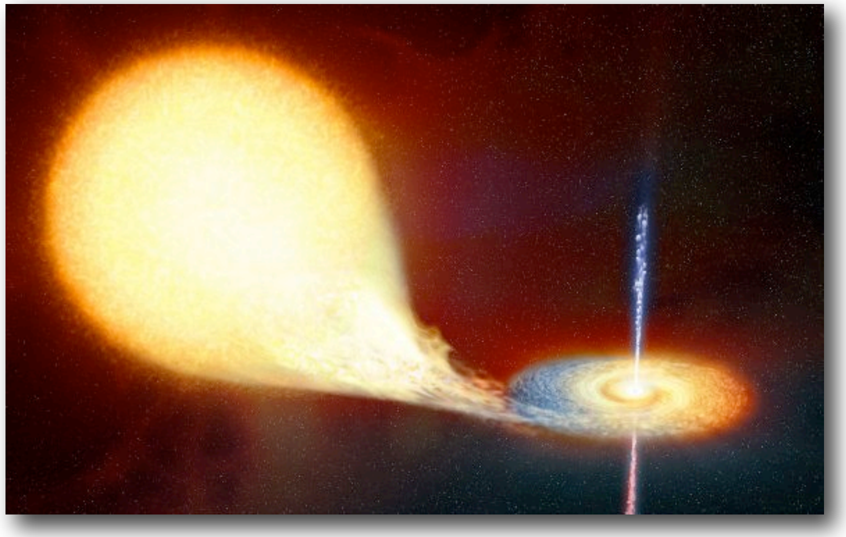
Physics with neutrino telescopes
(selected results and current sensitivities)

Perspectives for neutrino astronomy

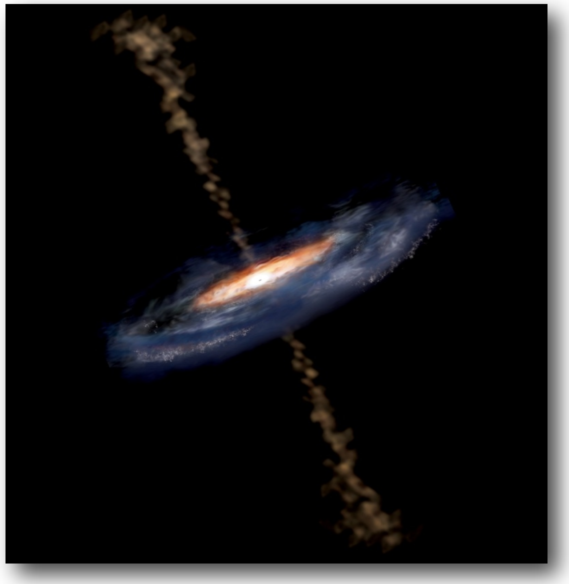
The high-energy universe

supernova remnants
(SN1006, optical, radio, X-ray)

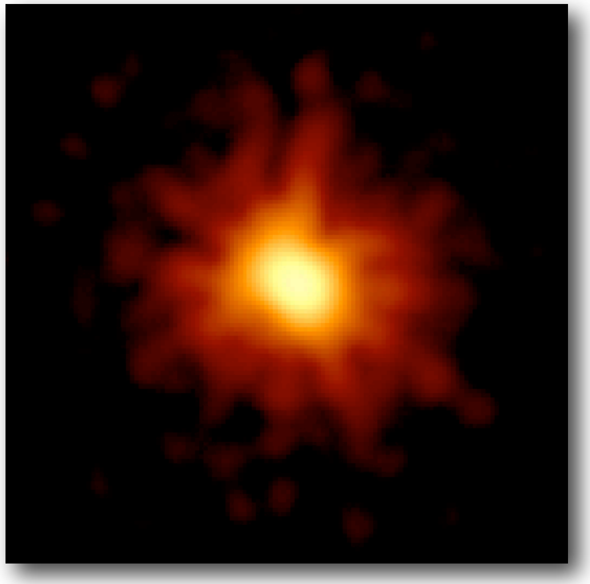
micro-quasars
(artist's view)



active galactic nuclei
(artist's view)



gamma-ray bursts
(GRB 080319B, X-ray, SWIFT)



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High-energy particle production in the universe

Accelerator (source)

- Shock fronts (Fermi acceleration)
- Objects with strong magnetic fields (pulsars, magnetars)

Beam dump (secondary particle production)

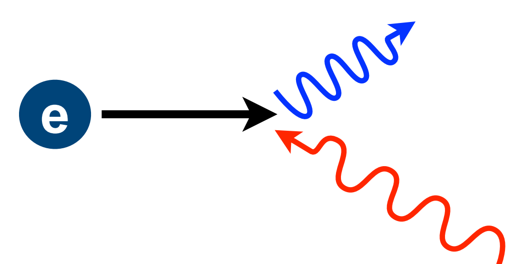
- Interaction with photons or matter
- Protons: pion decay

$$p + p(\gamma) \rightarrow \pi^{\pm} + X$$
$$\hookrightarrow \mu + \nu_\mu$$
$$\hookrightarrow e + \nu_\mu + \nu_e$$

$$p + p(\gamma) \rightarrow \pi^{0} + X$$
$$\hookrightarrow \gamma + \gamma \text{ (TeV)}$$

- Electrons: inverse Compton-scattering of photons

$$e + \gamma \rightarrow e + \gamma \text{ (TeV)}$$



Why neutrino astronomy?

- Neutrinos point back to the source
- Neutrinos travel cosmological distances
- Neutrinos escape from optically thick sources
- Neutrinos are a clear sign for hadron acceleration

Neutrinos provide complementary information to gamma-rays and protons

Estimating neutrino fluxes

- Photon ↔ neutrino connection:

$p + p \rightarrow \pi^0 + X$
↳ $\gamma + \gamma$

$p + p \rightarrow \pi^\pm + X$
↳ $\mu + \nu_\mu$
↳ $e + \nu_\mu + \nu_e$

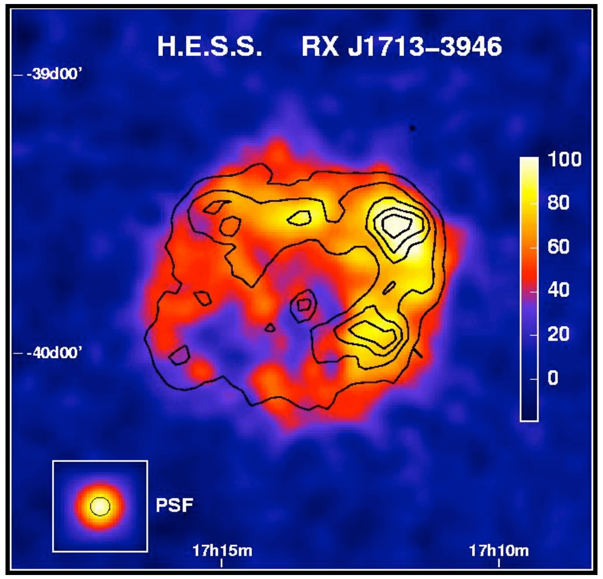
- Observed from RX J1713.7–3946 (SNR):
  - γ-rays up to several 10 TeV
    → particle acceleration up to 100 TeV and above

- Calculated neutrino fluxes:

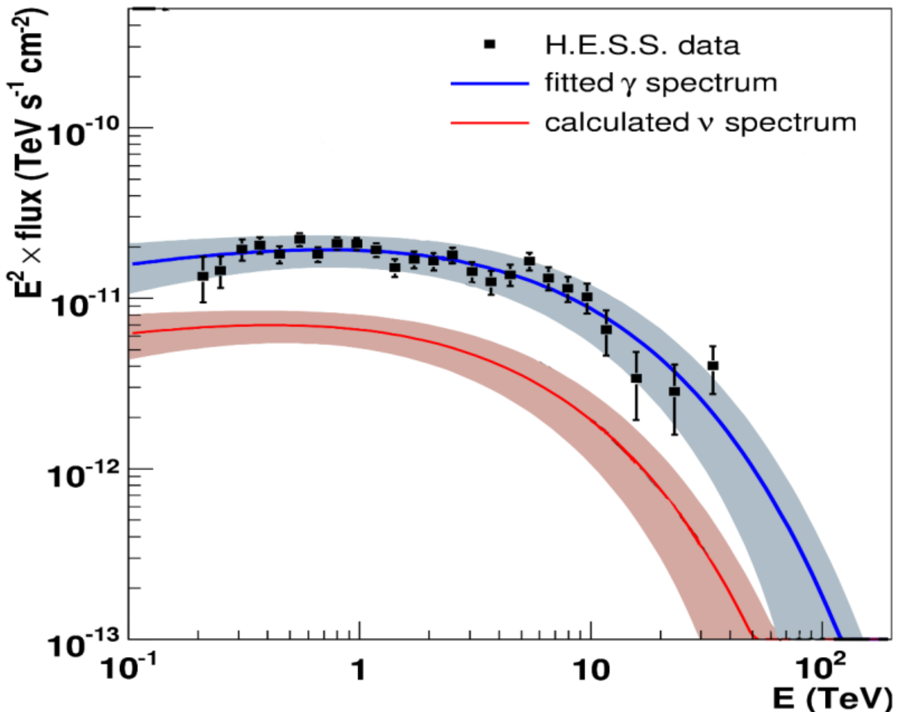
  For strong Galactic sources:

  10^{-12}–10^{-11} $\mathrm{TeV^{-1}\,cm^{-2}\,s^{-1}}$ @ 1 TeV

  AK, Hinton, Stegmann, Aharonian, ApJ (2006)
  Halzen, AK, O'Murchadha, PRD (2008)
  Kistler, Beacom, PRD (2006)
  . . .

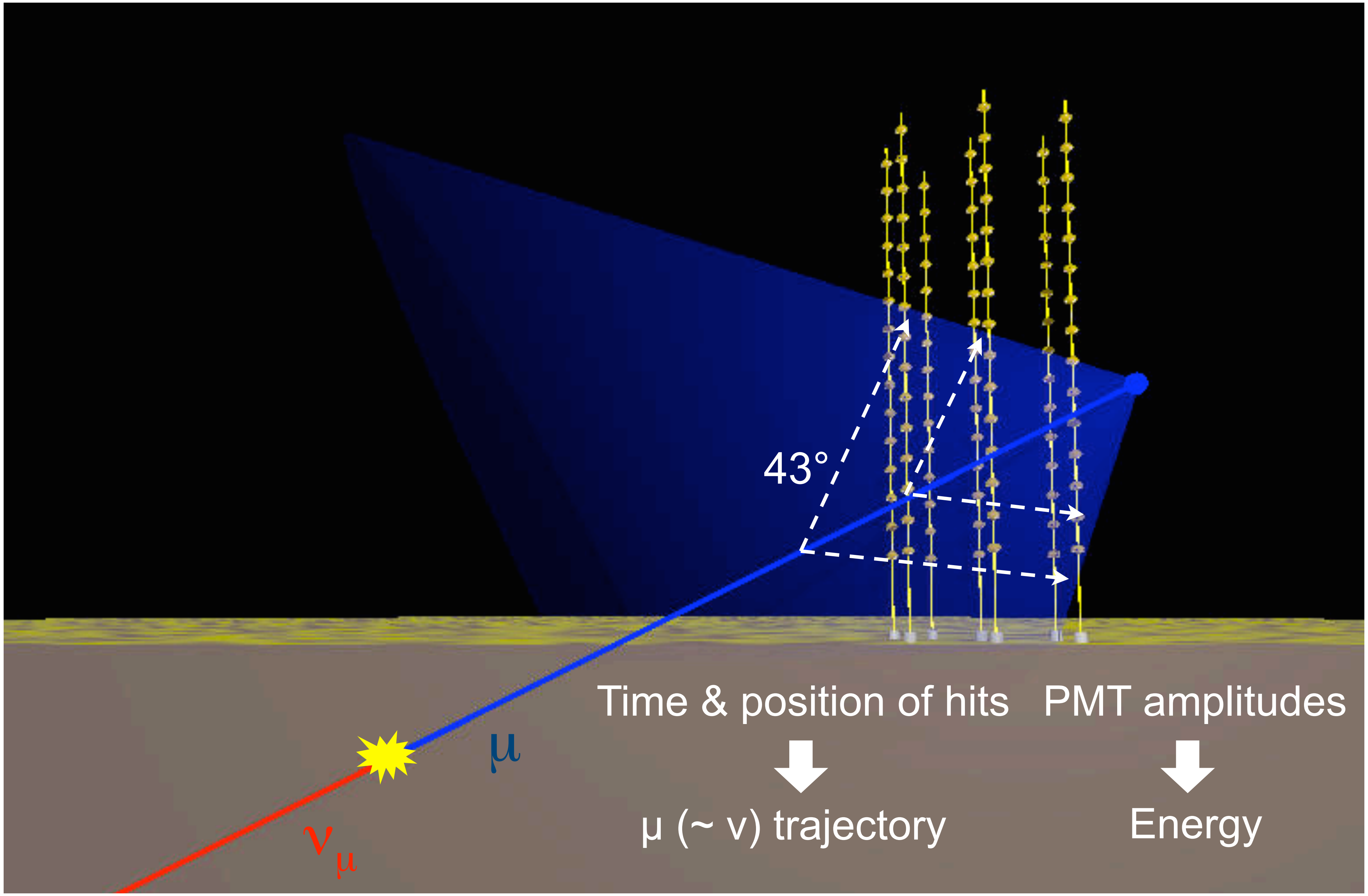


RX J1713.7–3946

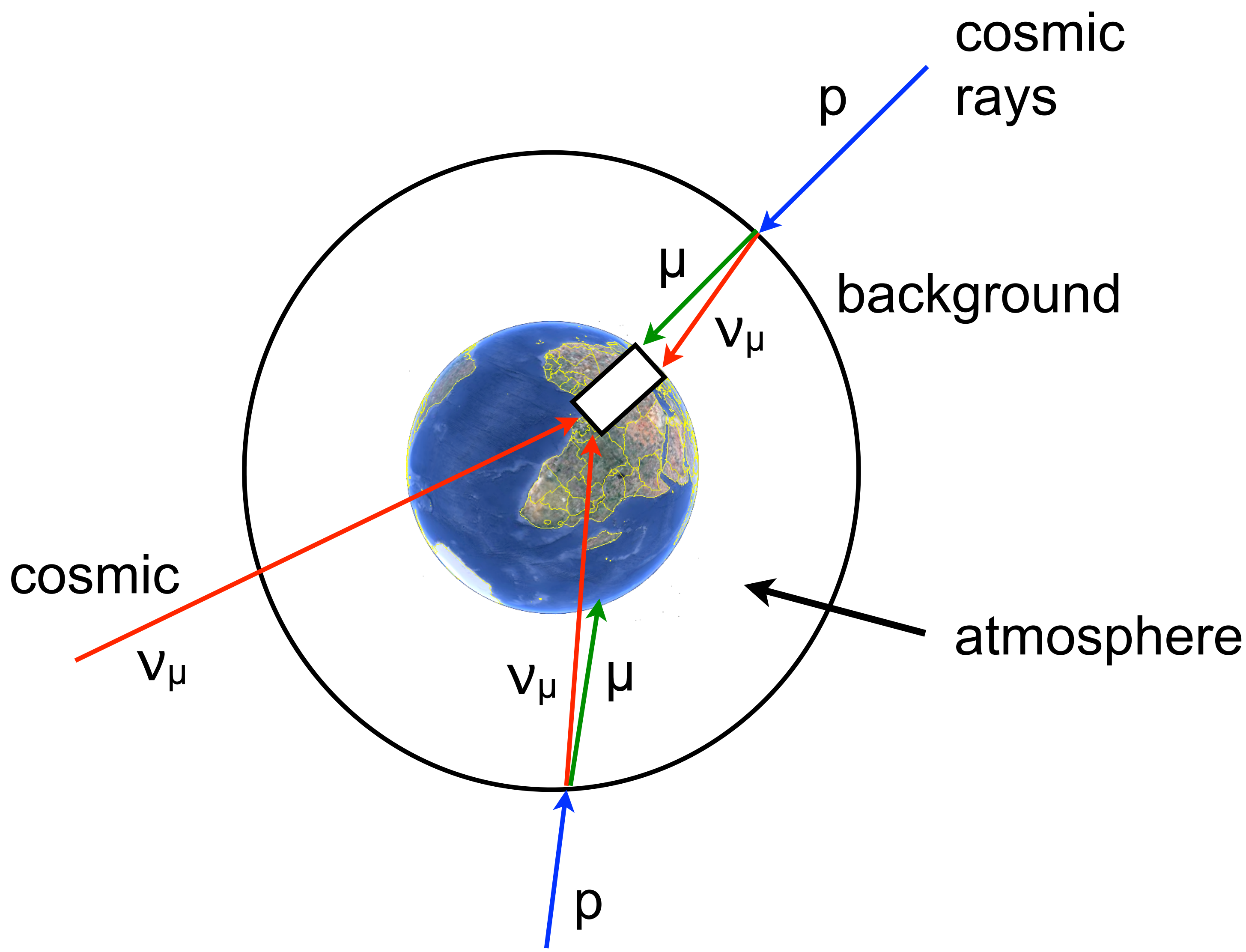


AK, Hinton, Stegmann, Aharonian, ApJ (2006)

Principle of neutrino detection



Background: atmospheric muons and neutrinos



- Flux from above dominated by atmospheric muons
- Neutrino telescopes mainly sensitive to neutrinos from below

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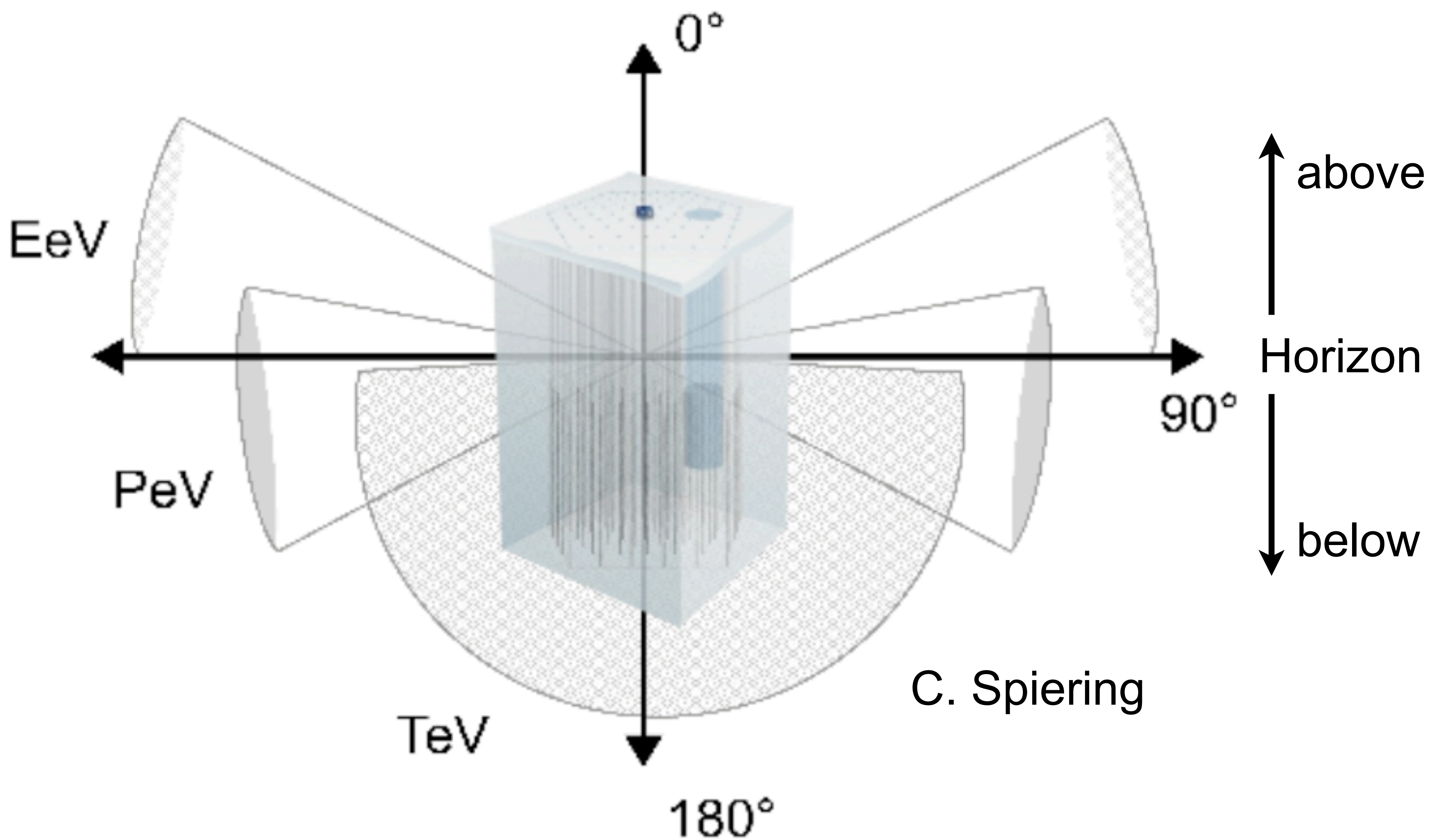
Sky visibility in neutrinos



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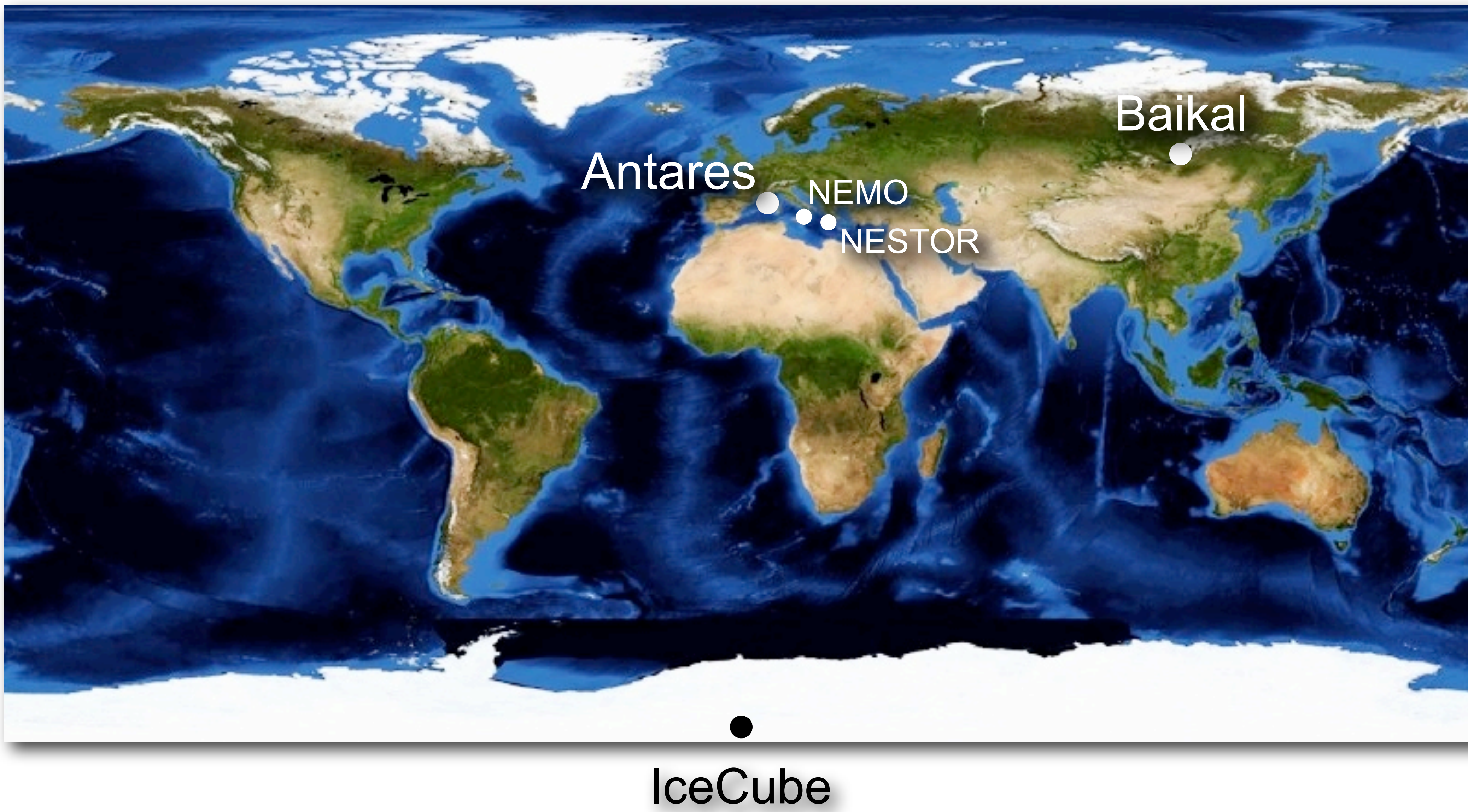
Currently operating Neutrino Telescopes

Neutrino telescope projects



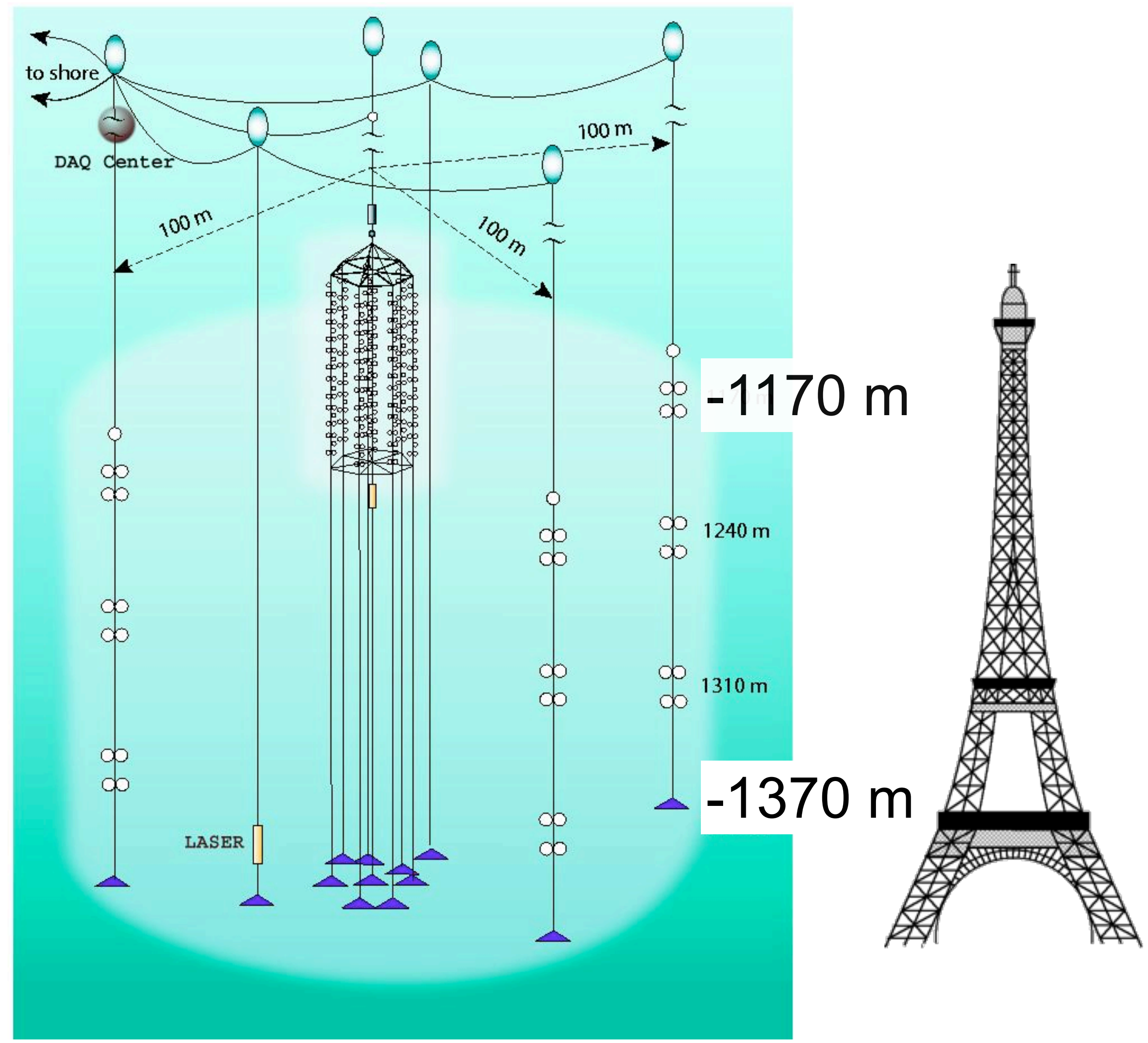
Baikal NT200(+)

NT200

- 8 strings (192 optical modules)
- Instrumented volume 10^{-4} km^3
- Running since 1998

NT200+

- NT200 + 3 outer strings
  (36 optical modules)
- Instrumented volume 0.004 km^3
- Running since 2005



Single storey

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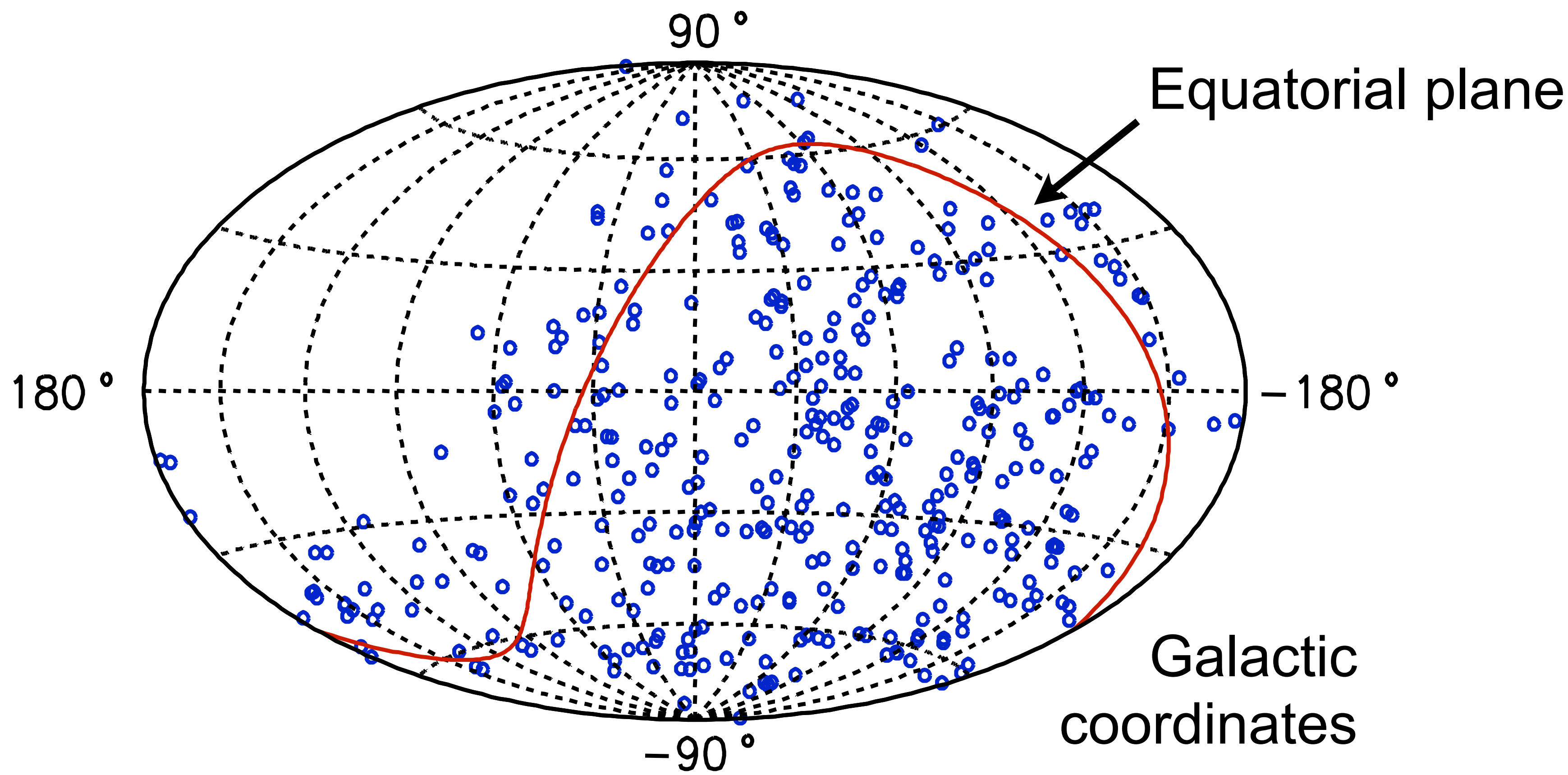
Baikal NT200: neutrino skymap

E_{thresh} = 15 – 20 GeV



- 372 neutrinos in 1038 days (1998-2003)
- 385 events expected from Monte Carlo
- No excess found

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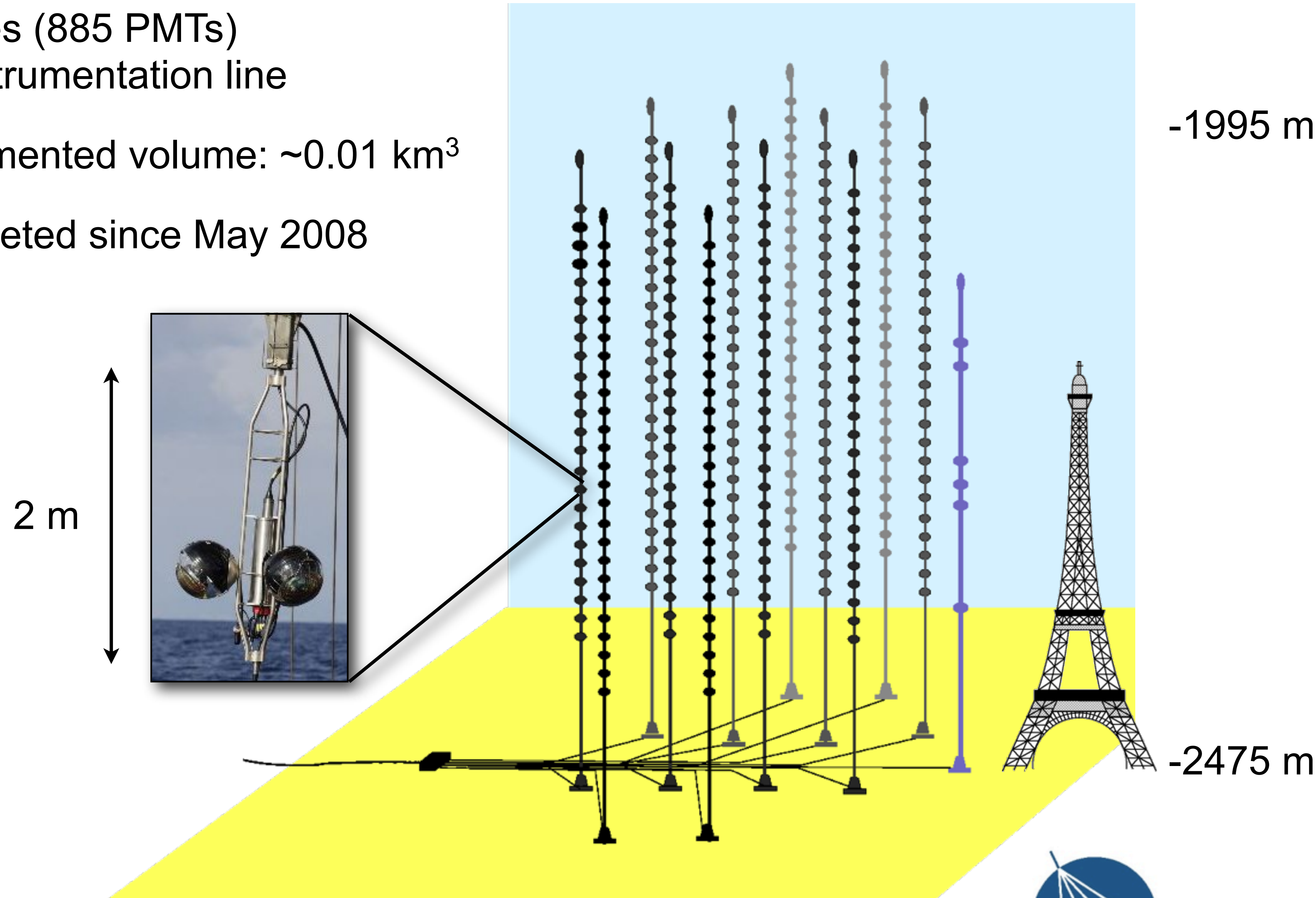
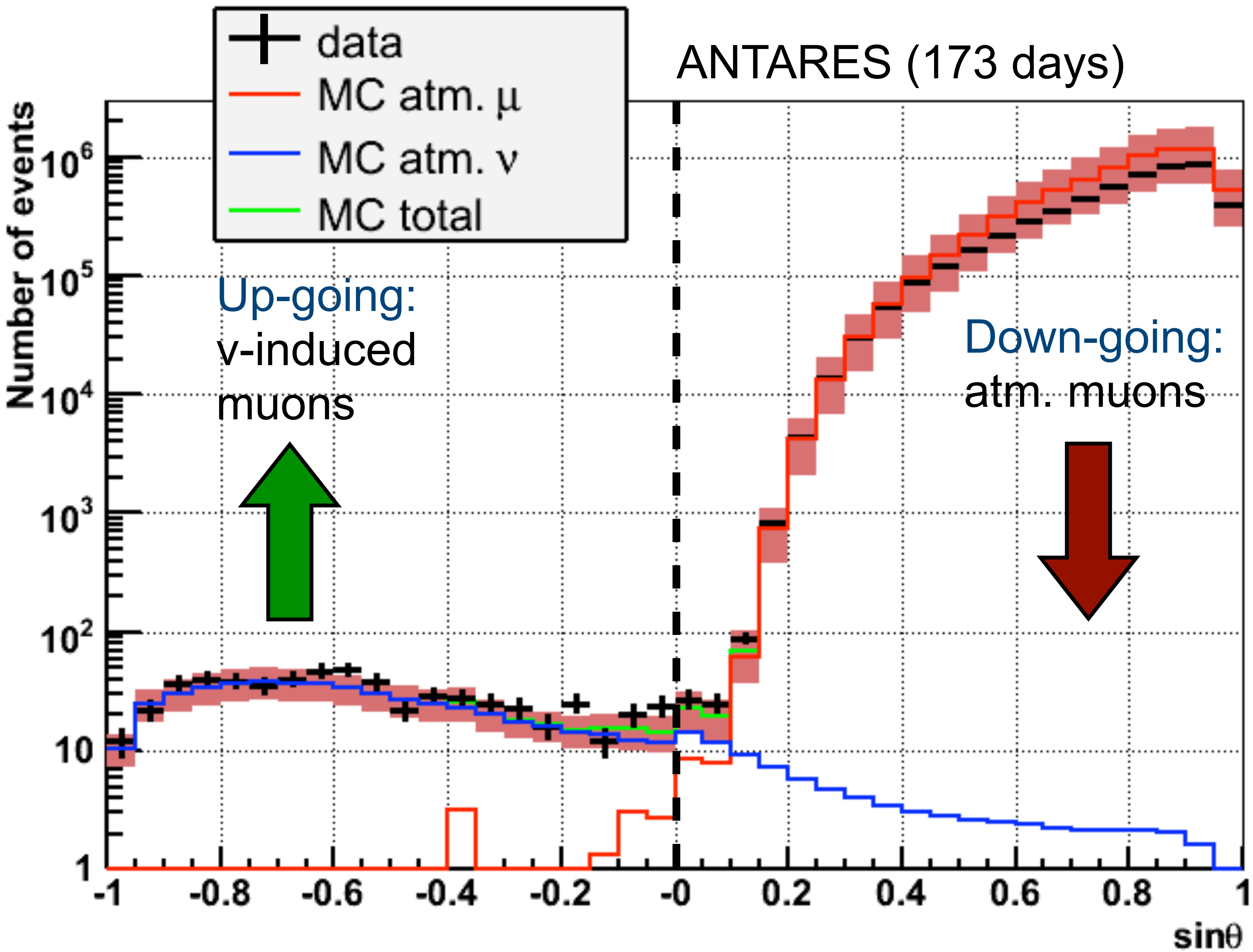
ANTARES

- 12 lines (885 PMTs)
  +1 instrumentation line
- Instrumented volume: ~0.01 km^3
- Completed since May 2008



Antares: atmospheric muons & neutrinos



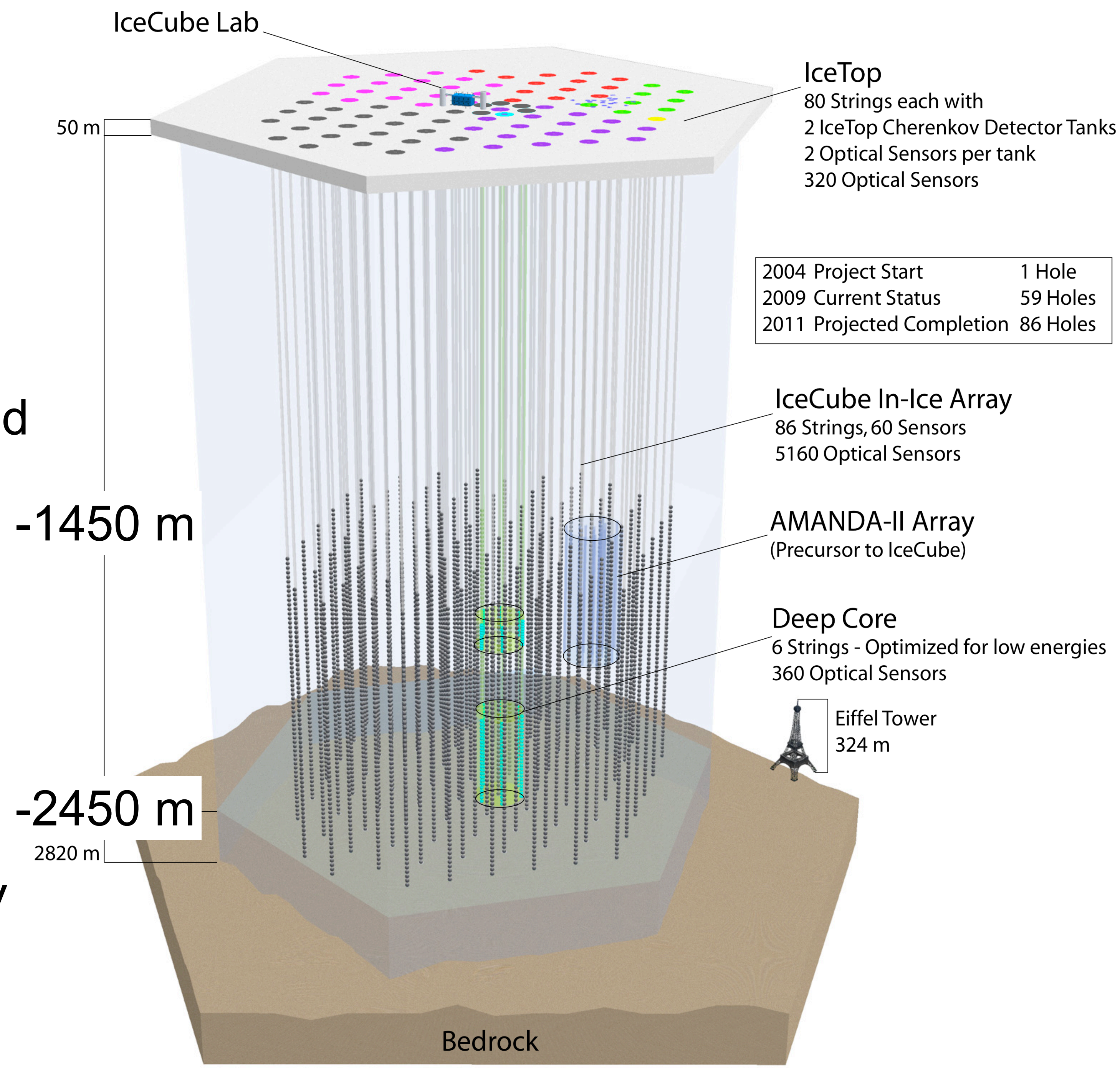
IceCube Observatory

- IceTop
  Air shower detector

- InIce
  80 strings (4800 PMTs)
  Status now: 58 strings deployed
  Instrumented volume: 1 km^3

- DeepCore
  6 additional strings
  More densely packed
  First string deployed 2008/09

  Low-energy physics, E < 1 TeV
  (WIMPS, . . .)



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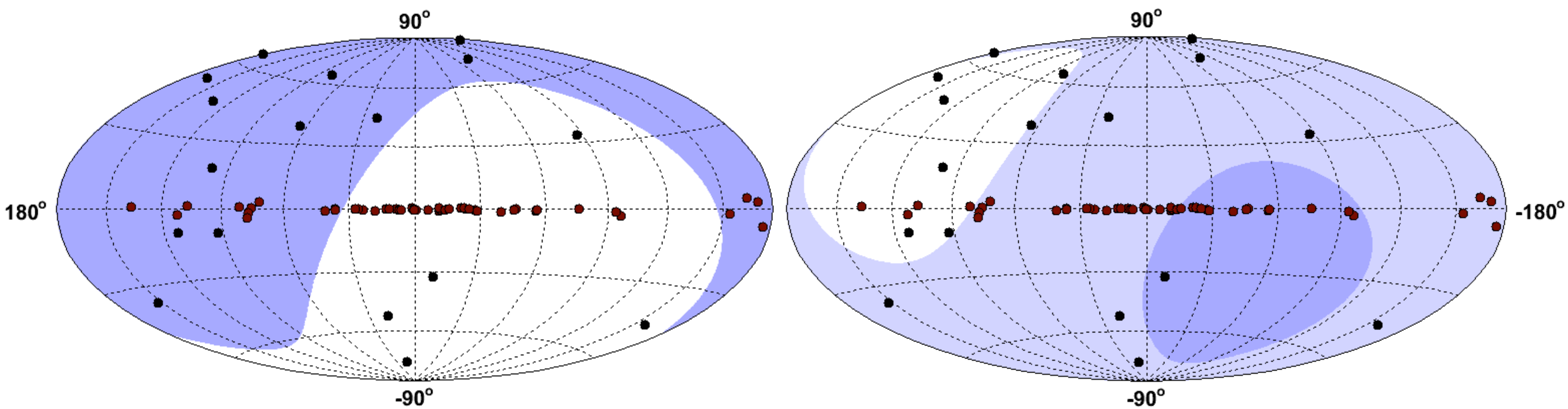
Sky coverage

Visibility IceCube (South Pole)
- 100%
- 0%

Visibility ANTARES (Mediterranean)
- > 75%
- 25% – 75%
- < 25%



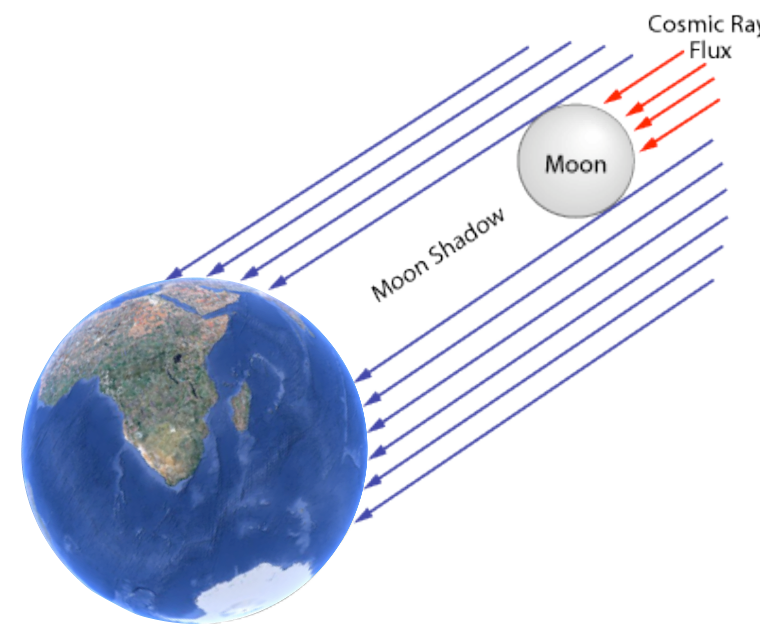
TeV γ-ray sources
- Galactic
- extra-Galactic

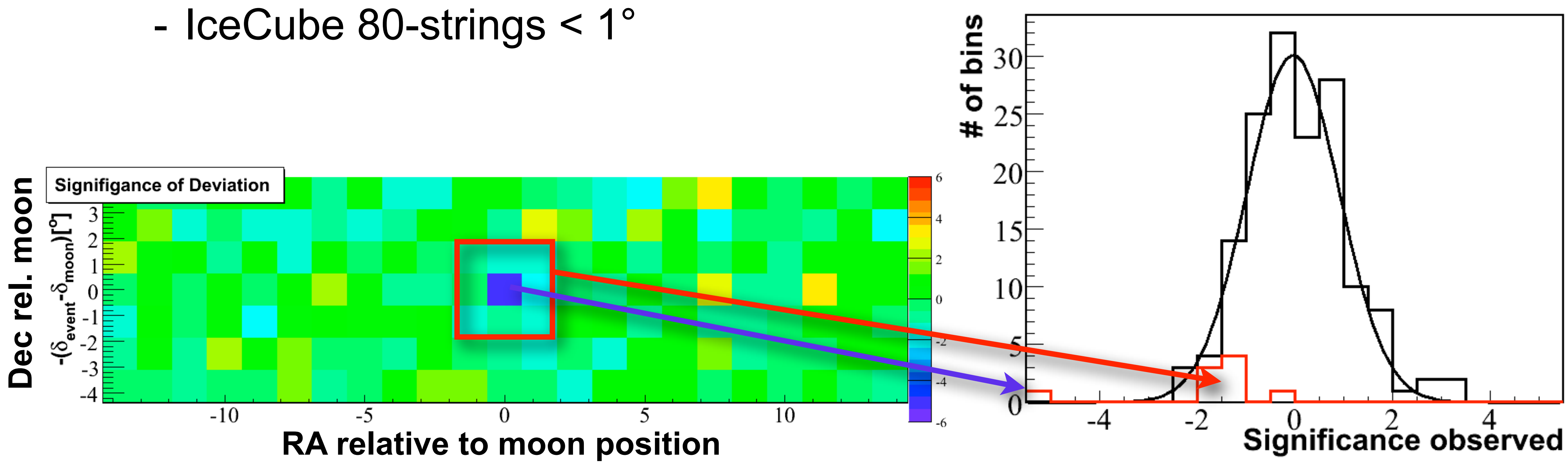
The Moon shadow (IceCube)

- No neutrino reference point-source to validate absolute pointing
- Use lack of atmospheric muons from Moon direction
  - Moon diameter 0.5°

  Angular resolution:

  - IceCube 80-strings < 1°





A. Karle @ ICRC 2009

Physics with Neutrino Telescopes
(selected results and sensitivities)

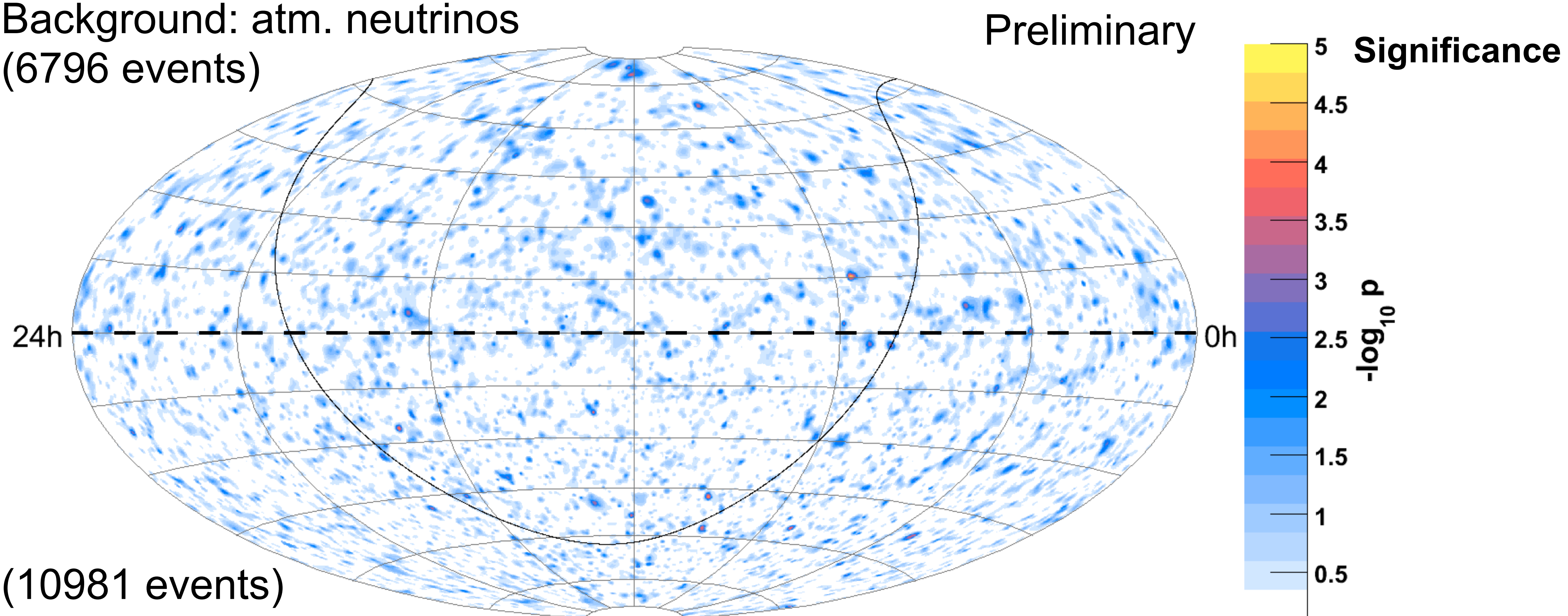
Physics with neutrino telescopes

- **Galactic sources**
  (Supernova remnants, Binary systems, Pulsar Wind Nebulae, . . .)
- **Extra-Galactic sources**
  (Gamma-ray Bursts, Active Galactic Nuclei, Supernovae)
- **Dark Matter**
  (WIMPs)
- **Diffuse neutrino flux**
- **Cosmogenic neutrinos (EeV)**
  (GZK, Top-down, . . .)

- Supernovae (MeV neutrinos)
- Neutrino oscillations (atmospheric neutrinos 10 - 100 GeV)
- Cosmic-ray anisotropy (atm. muons)
- Exotic physics (Lorentz violation, monopoles, . . .)

Search for point sources – IceCube 40 strings (6 months)

Background: atm. neutrinos
(6796 events)



(10981 events)
Background: atm. muons

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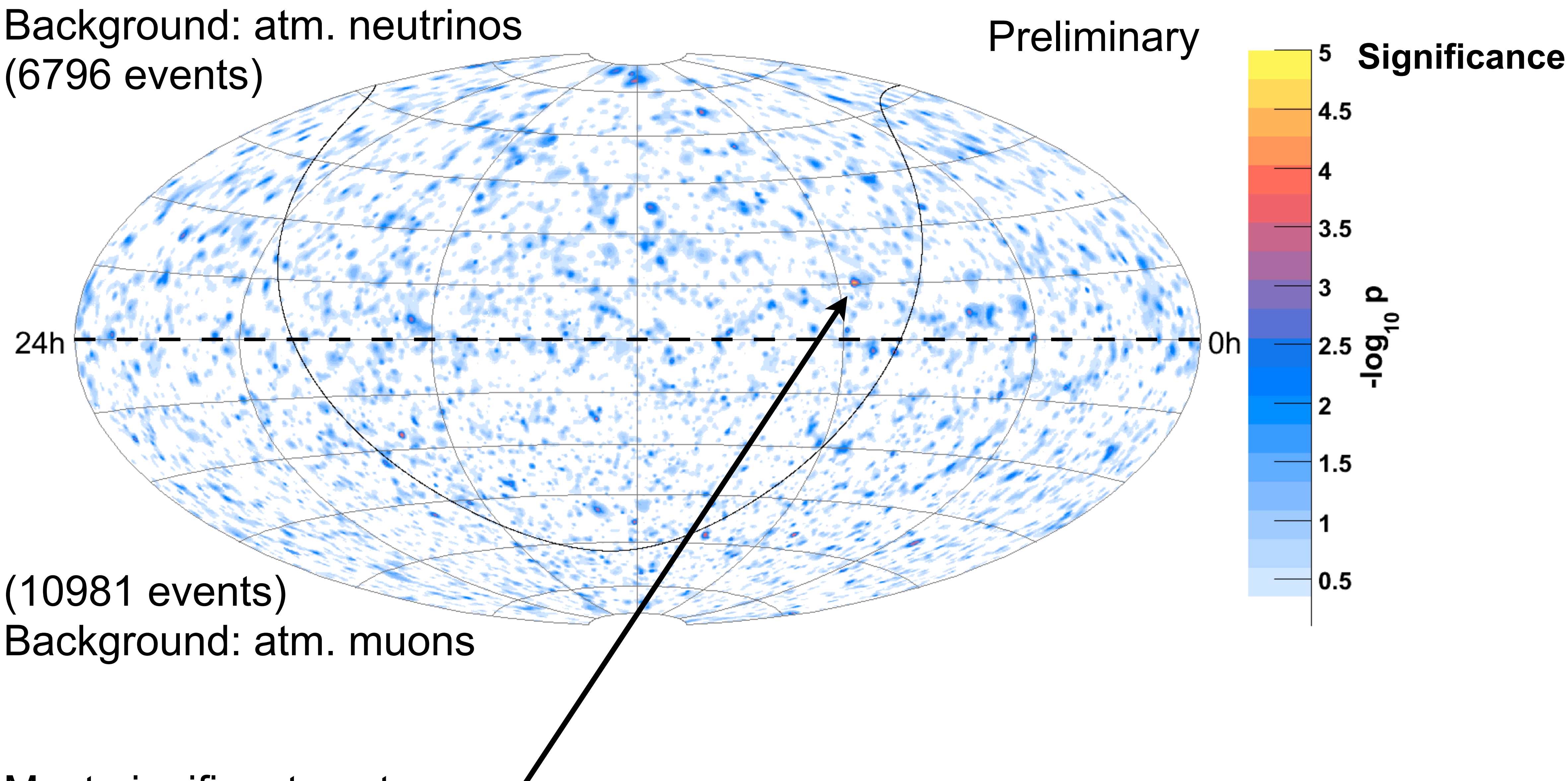
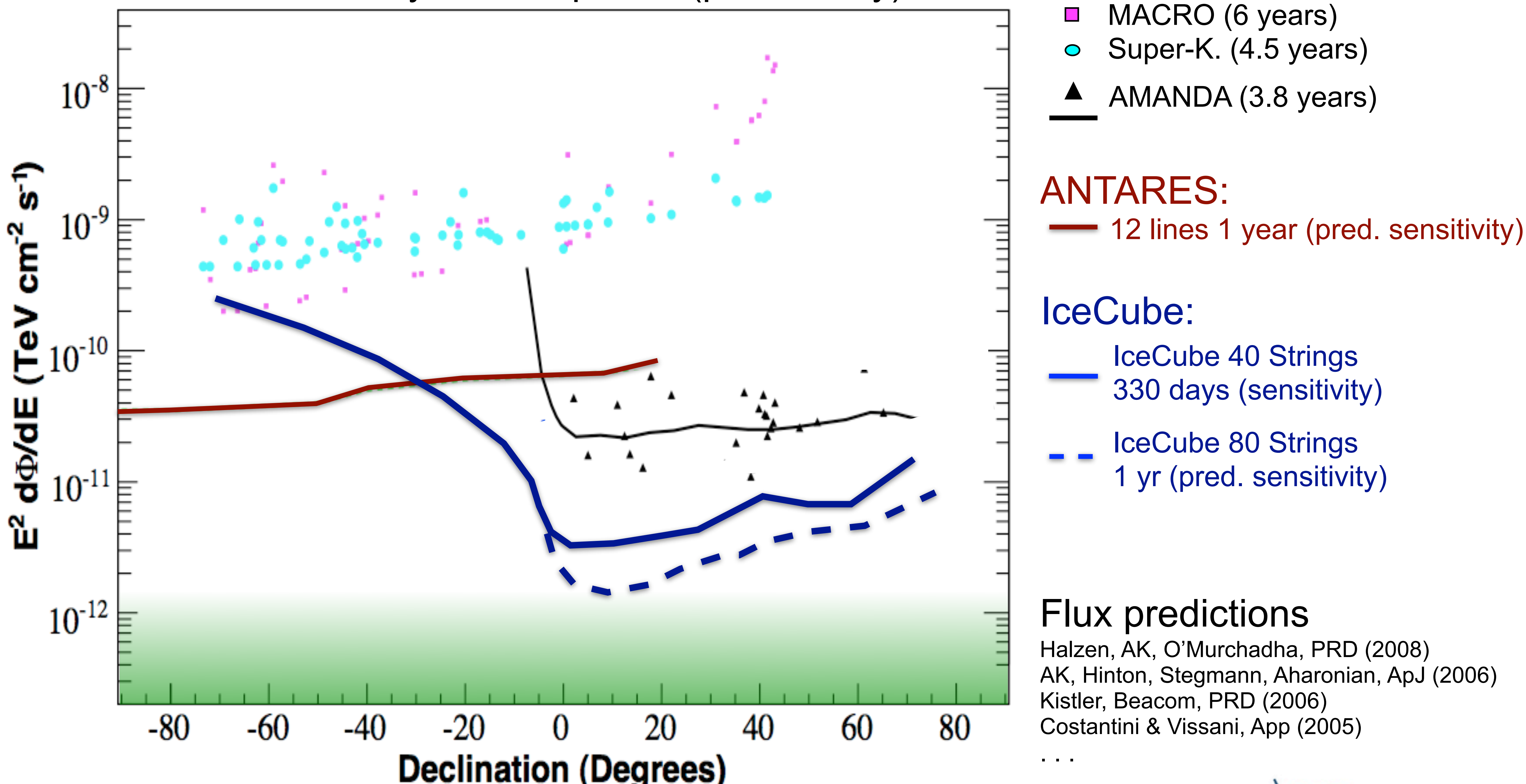
Search for point sources – IceCube 40 strings (6 months)



Most-significant spot:
all-sky background probability: 61%

Point source sensitivities

90% CL sensitivity for E^{-2} spectra (preliminary)



Flux predictions

Halzen, AK, O'Murchadha, PRD (2008)
AK, Hinton, Stegmann, Aharonian, ApJ (2006)
Kistler, Beacom, PRD (2006)
Costantini & Vissani, App (2005)
. . .

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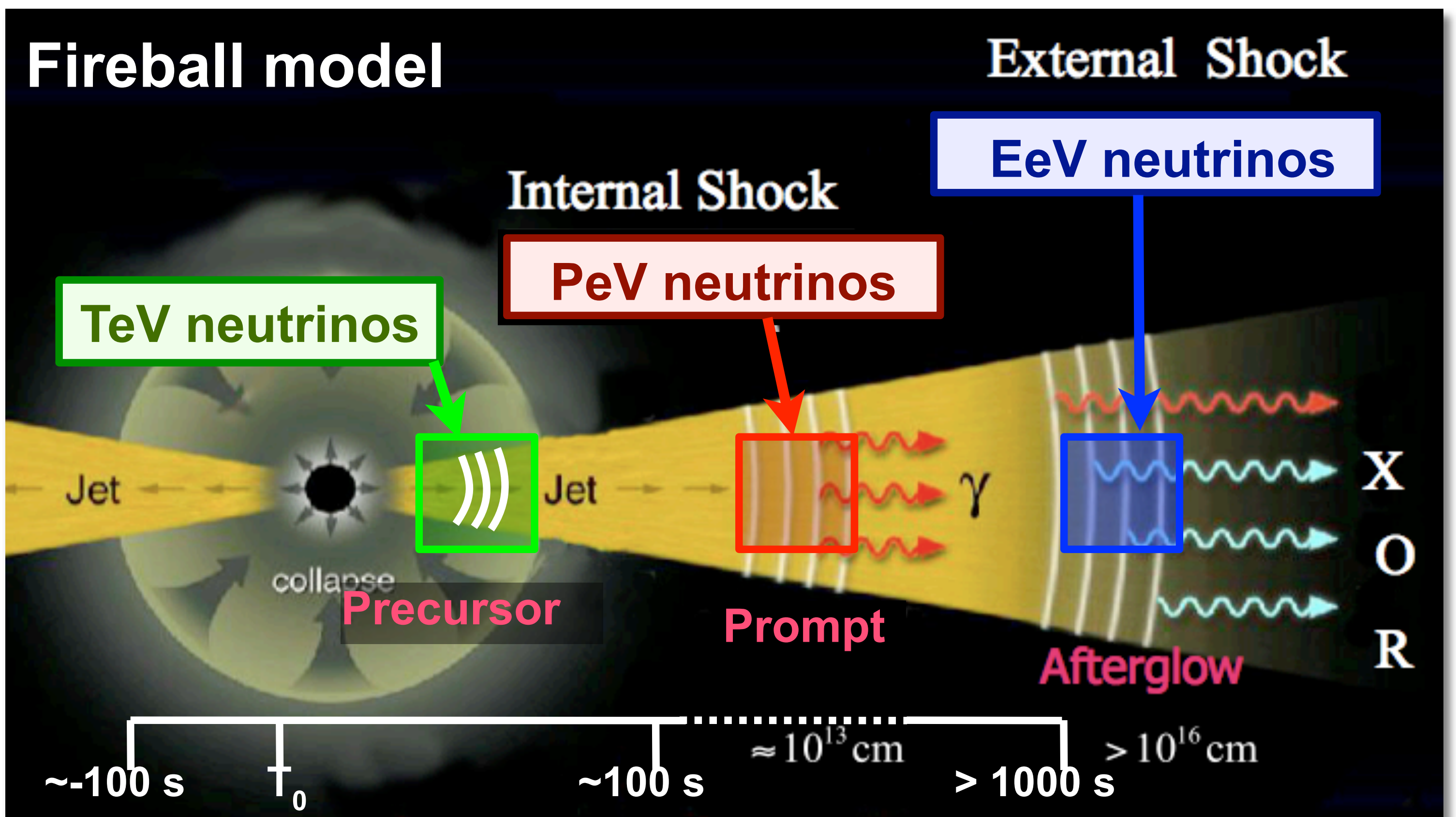
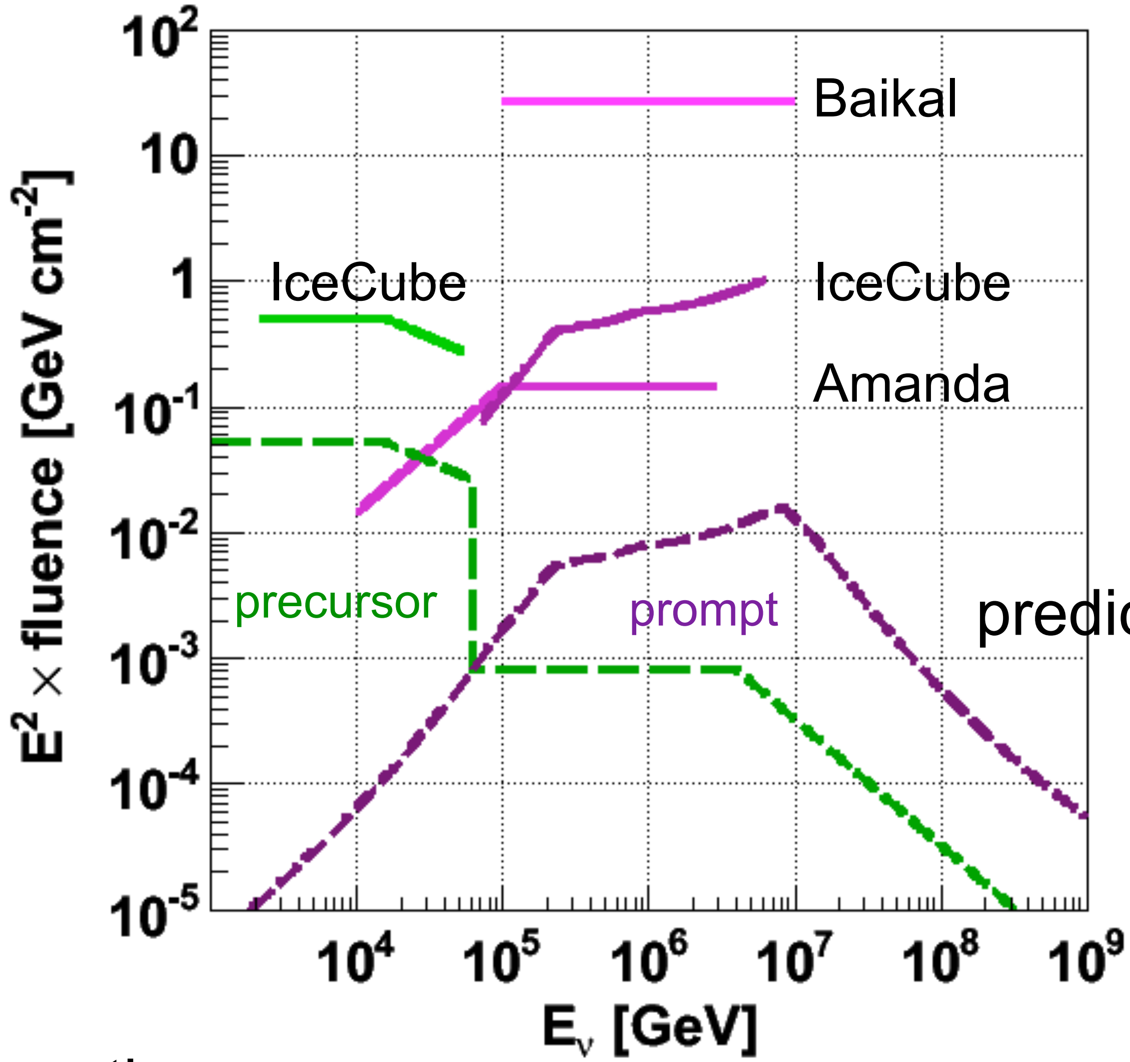
Gamma-Ray Bursts

- Gamma-ray signal observed by satellites (e.g. Fermi, SWIFT)
- Neutrino searches profit from known time and direction
- Low number of events per burst expected → burst stacking



Limits on neutrino fluxes from GRBs



- Baikal NT200+ (155 GRBs)
  (Avrorin et al., arXiv:0910.4327)
- IceCube 22-strings (41 GRBs)
  (Abbasi et al, arXiv:0907.2227)
- AMANDA (417 GRBs)
  (Achterberg et al. (2008) ApJ 674, 357)

predictions

precursor: Meszaros & Waxman, PRL (2001)
prompt: IceCube, AK et al., ICRC2009

Perspectives:

- 200 – 300 GRBs per year (Fermi, SWIFT)
- IceCube will be able to detect predicted fluxes within next years

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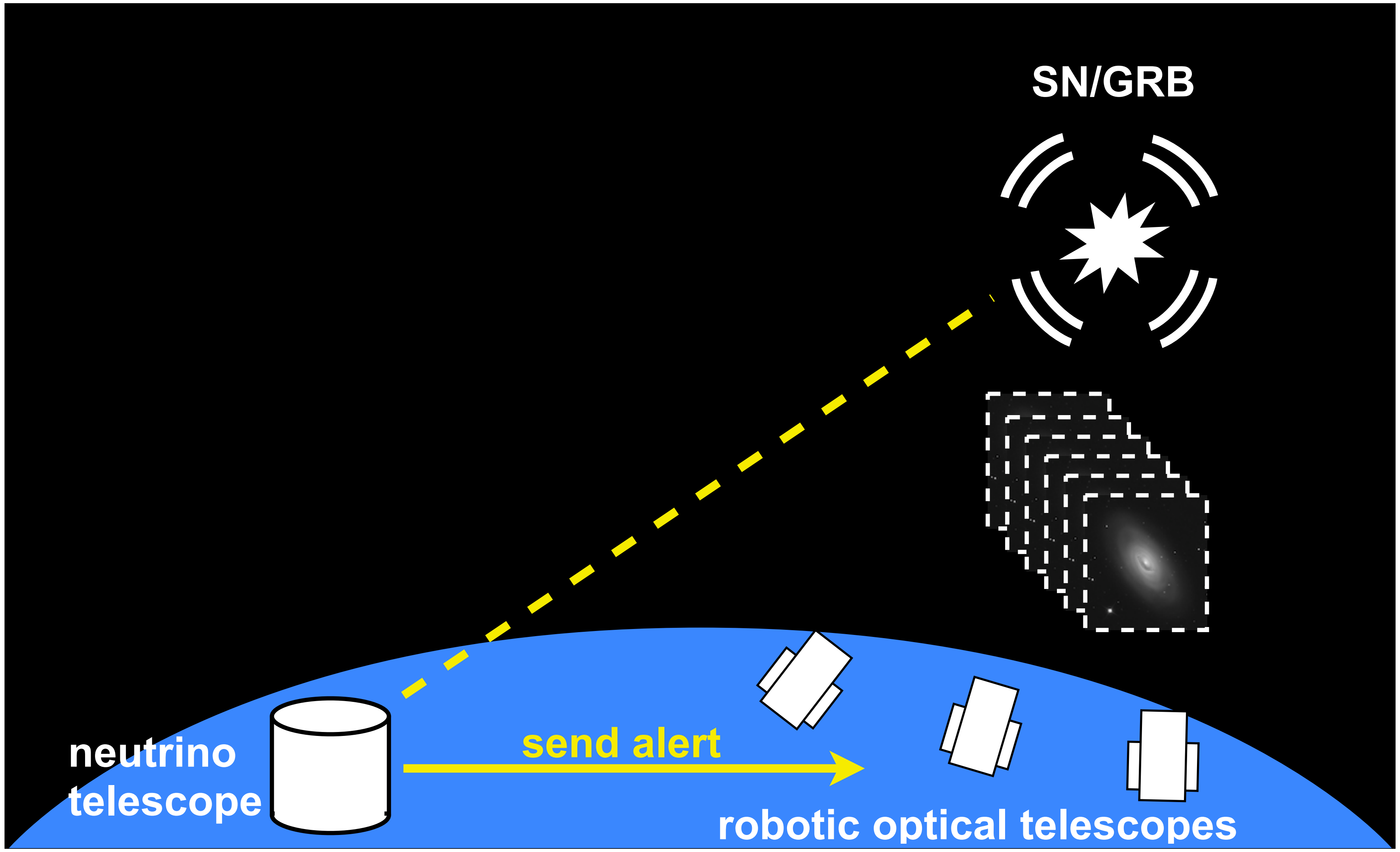
Optical Follow-Up

- First proposed by M. Kowalski (Kowalski and Mohr (2007), App 27, 533)

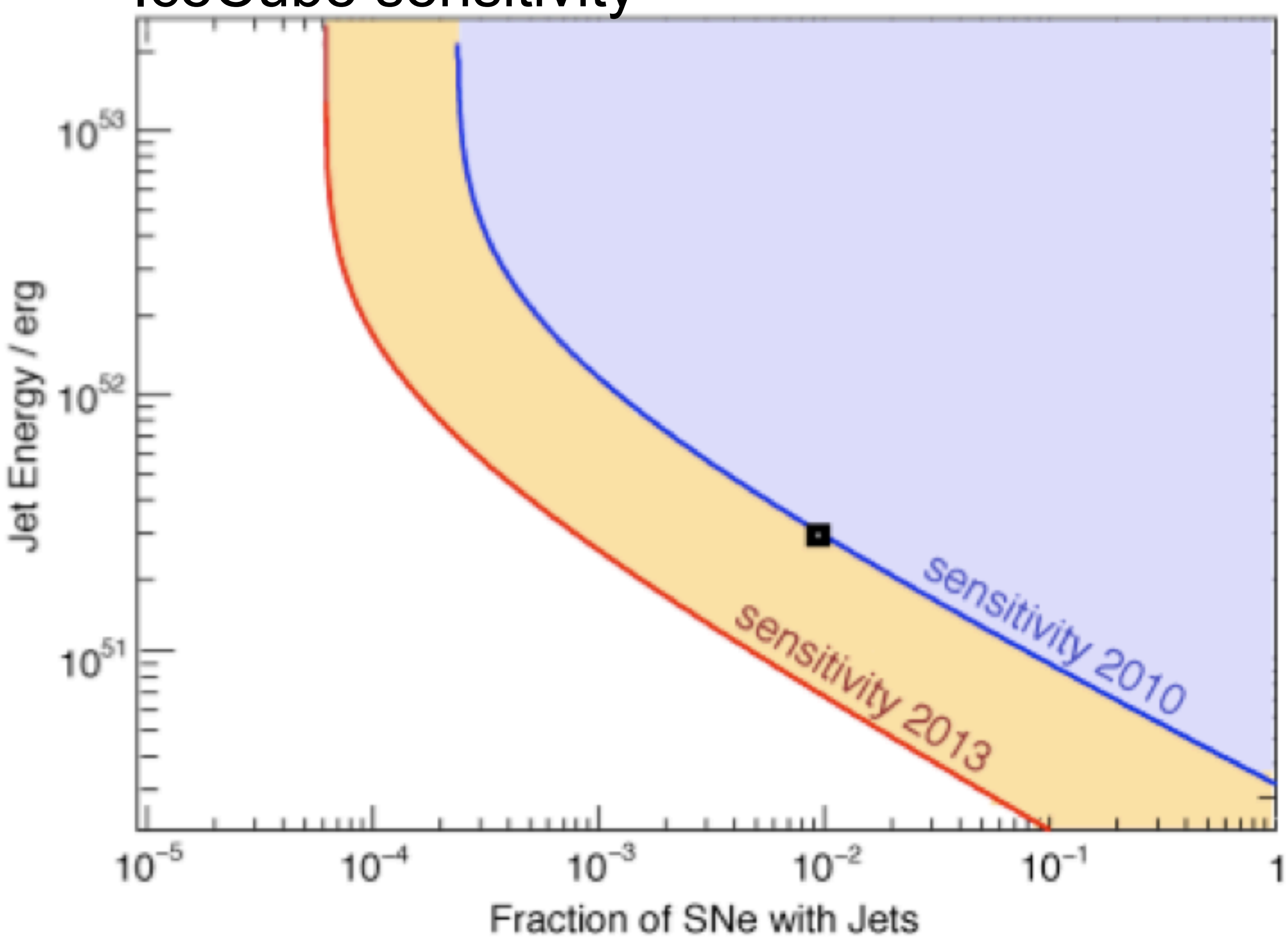


- IceCube: cooperation with ROTSE (4 telescopes)
- Antares: cooperation with TAROT (2 telescopes)

Optical follow-up: IceCube sensitivities

- Potentially large fraction of core-collapse SNe with stuck jets
  → no γ-ray signal
- 30 neutrino events expected in IceCube for SN @ 10 Mpc
  (Ando & Beacom, PRL (2005), Razzaque, Meszaros & Waxman, PRL (2005))

IceCube sensitivity



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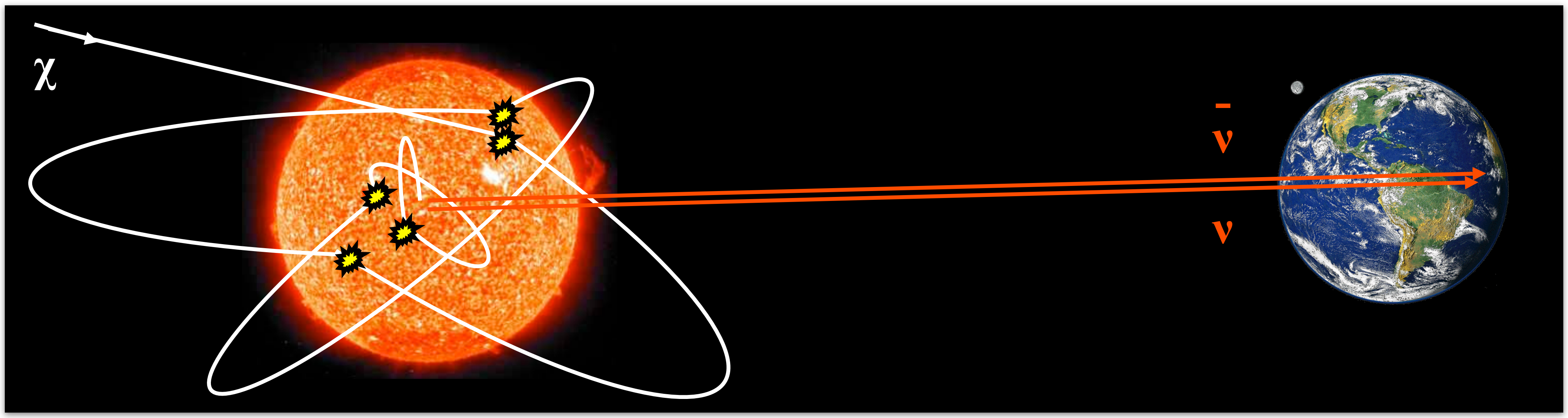
Dark Matter Searches (WIMPs)

- Neutralino (χ) good WIMP candidate
- Gravitational capture in the Sun followed by self annihilation



- Neutrino rate only depends on scattering cross section (equilibrium between capture and annihilation)

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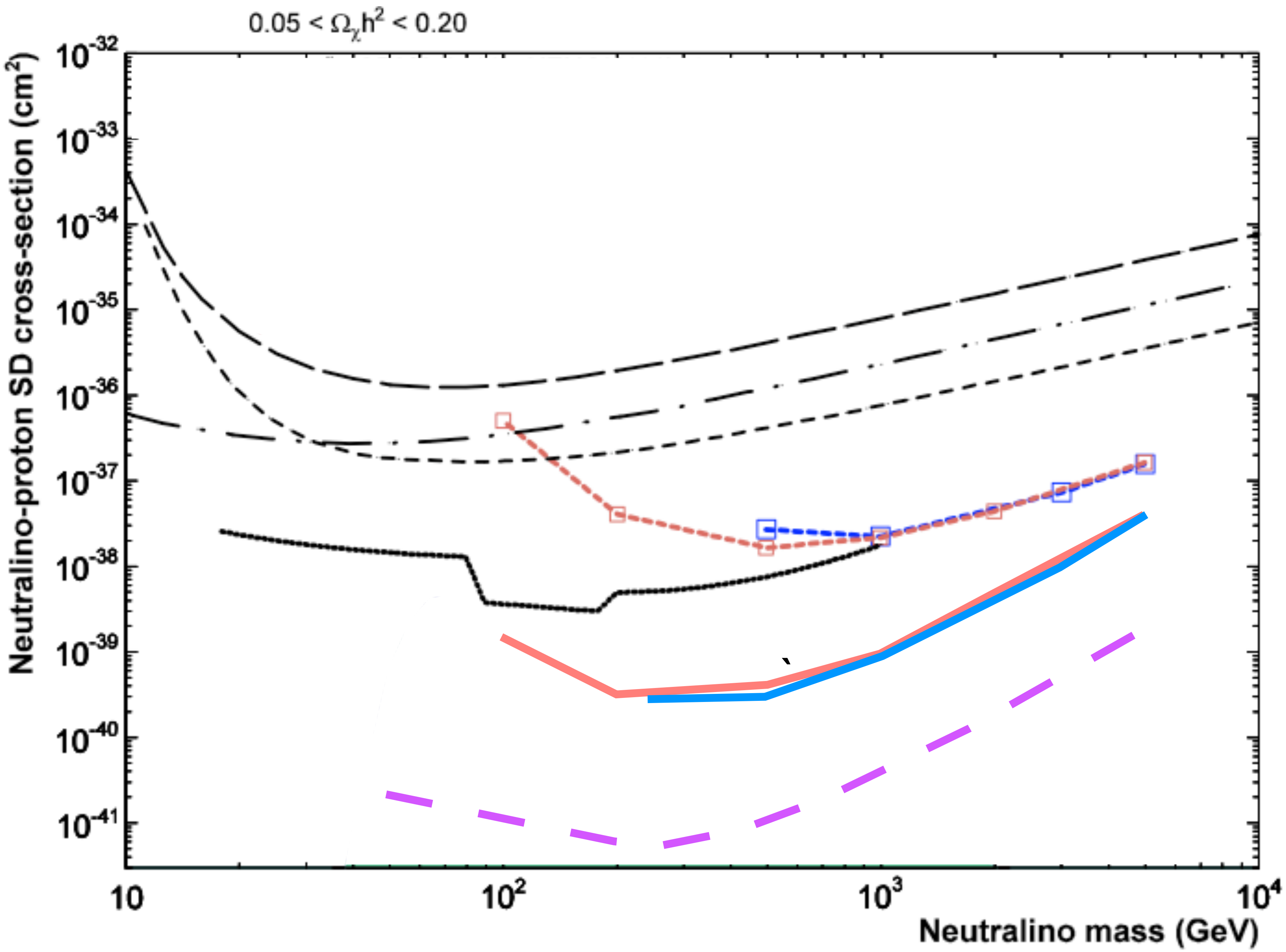
WIMP searches



Direct detection experiments (CDMS, COUPP, KIMS)

AMANDA 7 years
- soft
- hard

Super-Kamiokande (2004)

IceCube 22-strings limits (PRL 102, 201302 (2009))
- soft
- hard

IceCube 86 with Deep Core Sensitivity 1 yr (prel., hard)

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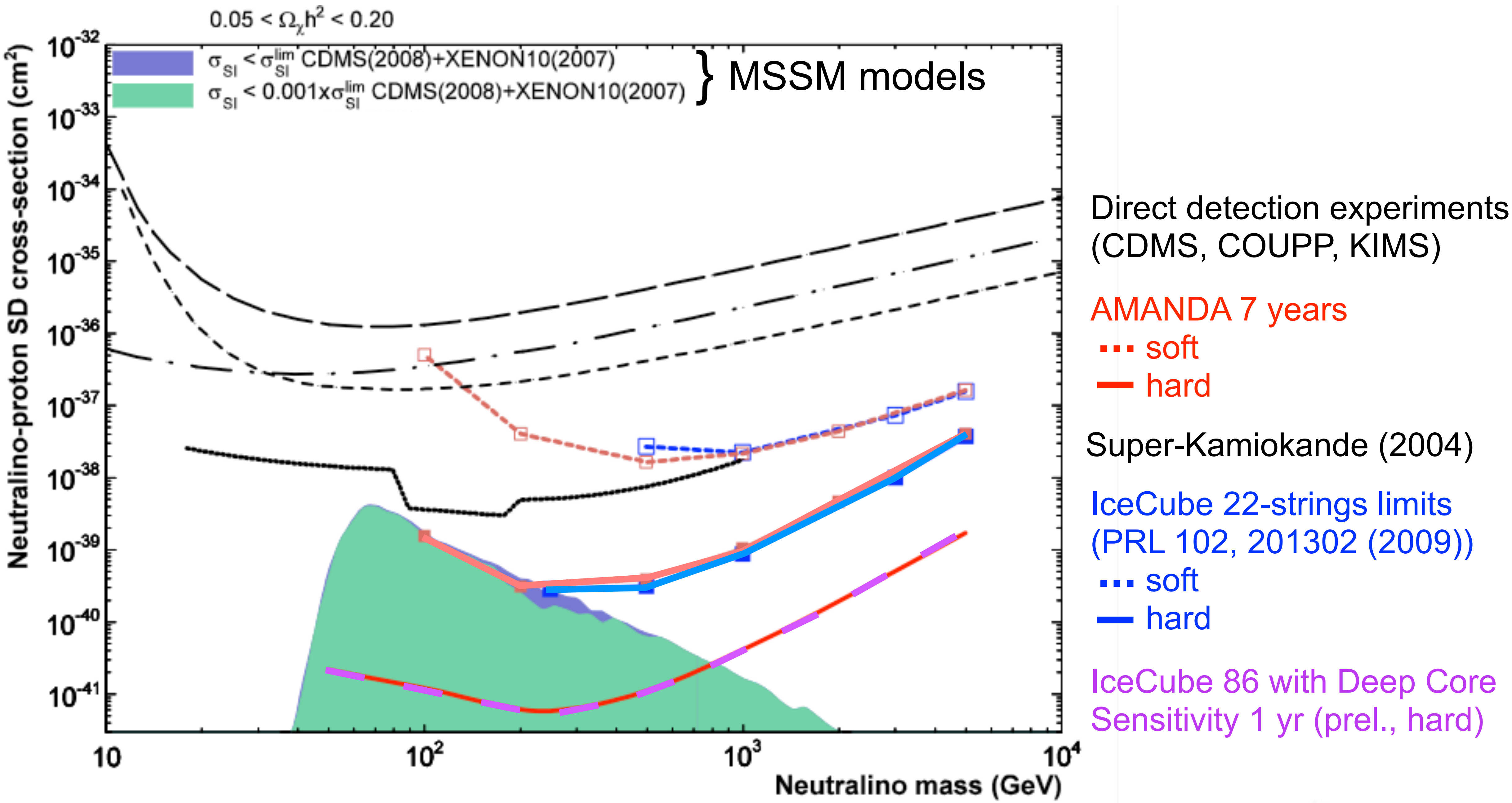
WIMP searches



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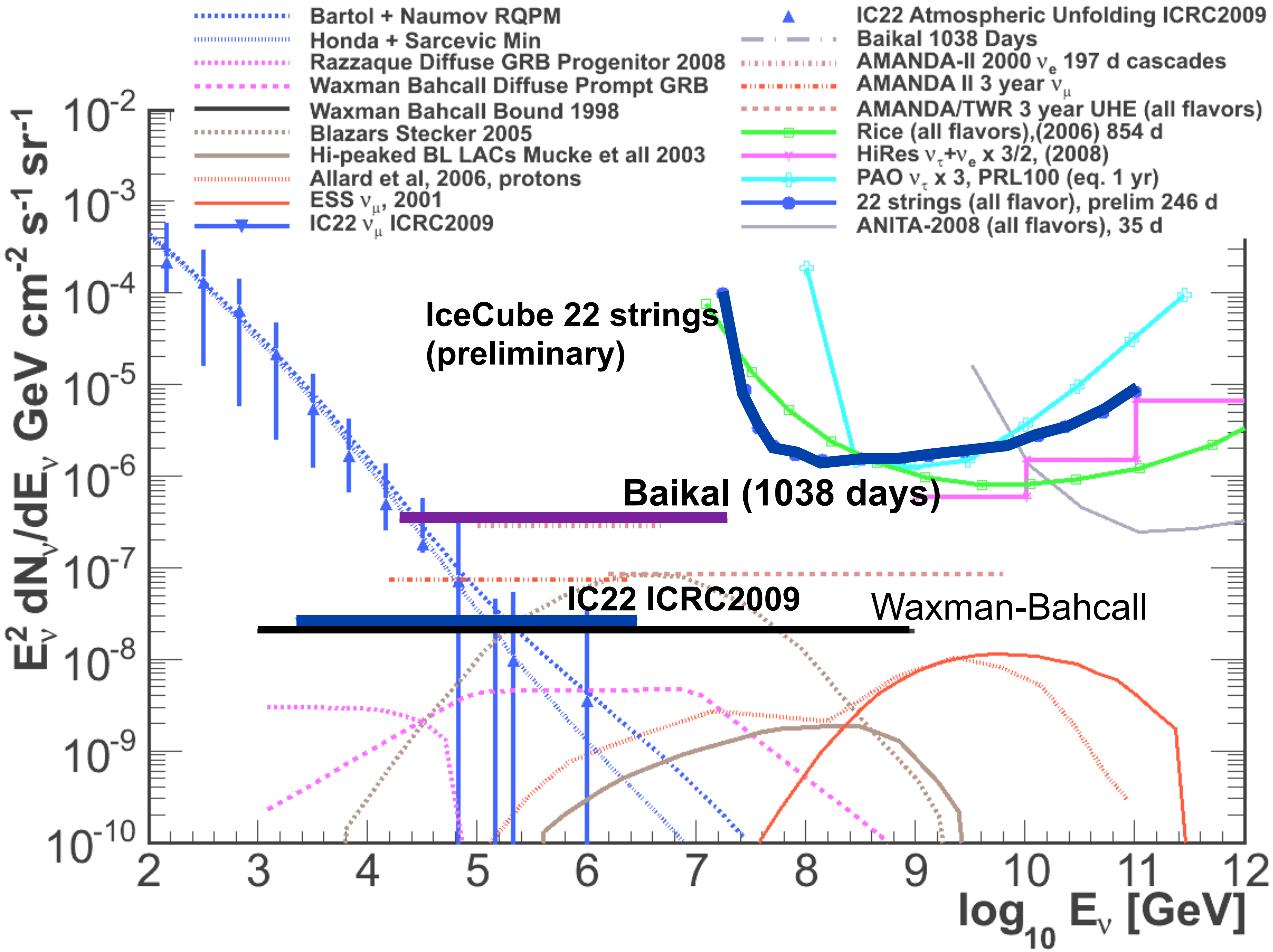
Diffuse neutrino flux



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Summary current status

- Main mission of neutrino telescopes:
  discovery of cosmic high-energy neutrino sources

- 3 active neutrino telescopes (Antares, Baikal, IceCube)

- IceCube currently most sensitive detector
  - covers only northern hemisphere (with high sensitivity)
  - will start to test model fluxes within next years

- Antares and Baikal significantly less sensitive
  - cover southern hemisphere (and part of northern hemisphere)
  - only minimal chances for discovery

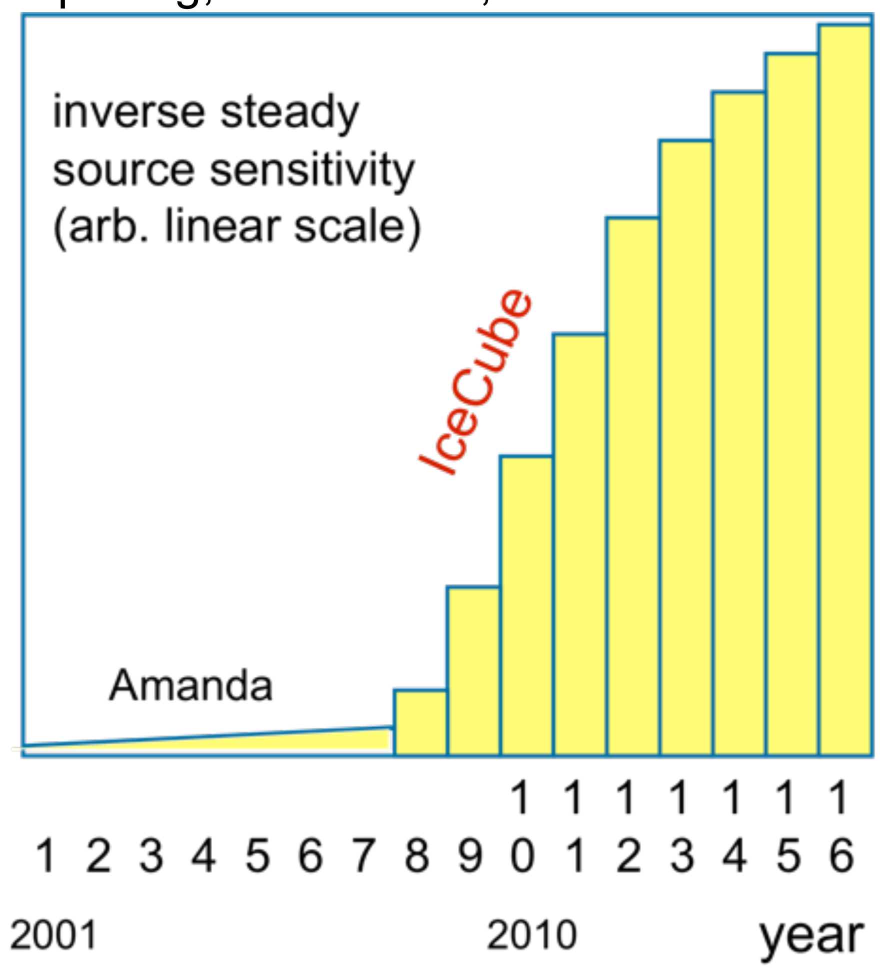
Perspectives for Neutrino Astronomy

Sensitivity increase in next years

- IceCube:
  Factor 25 increase in sensitivity compared to AMANDA 7 years
  - Increased detector size and quality
  - Cumulative data taking time
  - Improved analysis methods

- IceCube enters region with realistic discovery potential

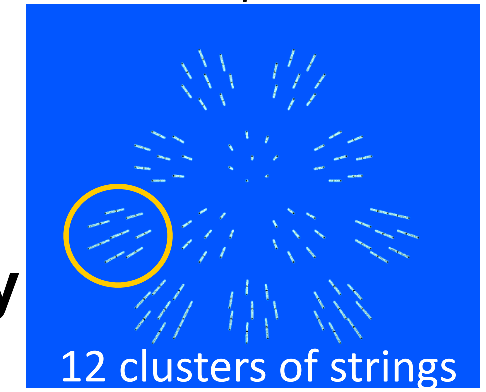
Spiering, HGF review, 2009



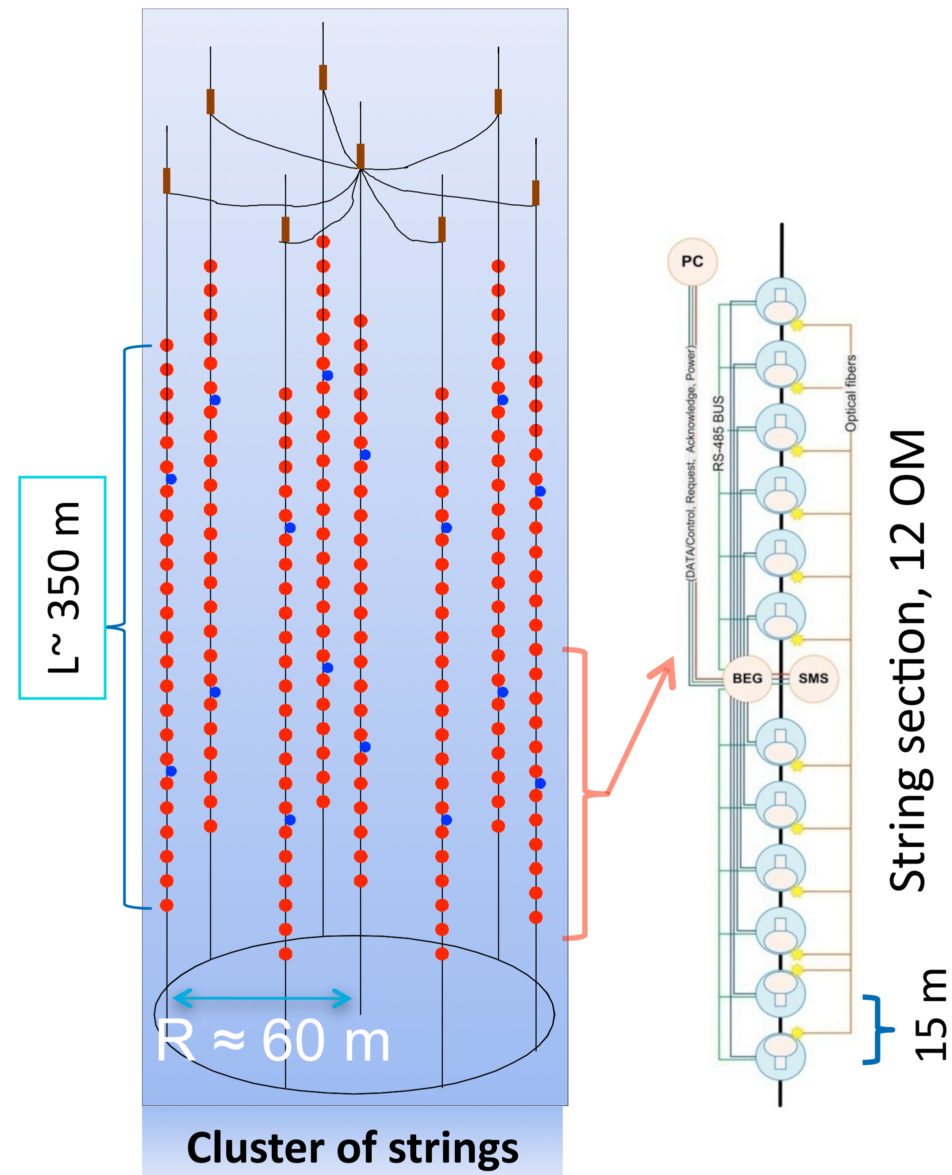
but flux predictions suggest that it might only scratch discovery region
. . . and it covers only half the sky

Baikal Gigaton Volume Detector

NT1000: top view



Preliminary Design



Currently in R&D phase
(Technical Design Report expected in 2011)

Layout:

- ~2300 Optical Modules on 96 strings
- 24 OMs per string
- Strings combined in Clusters

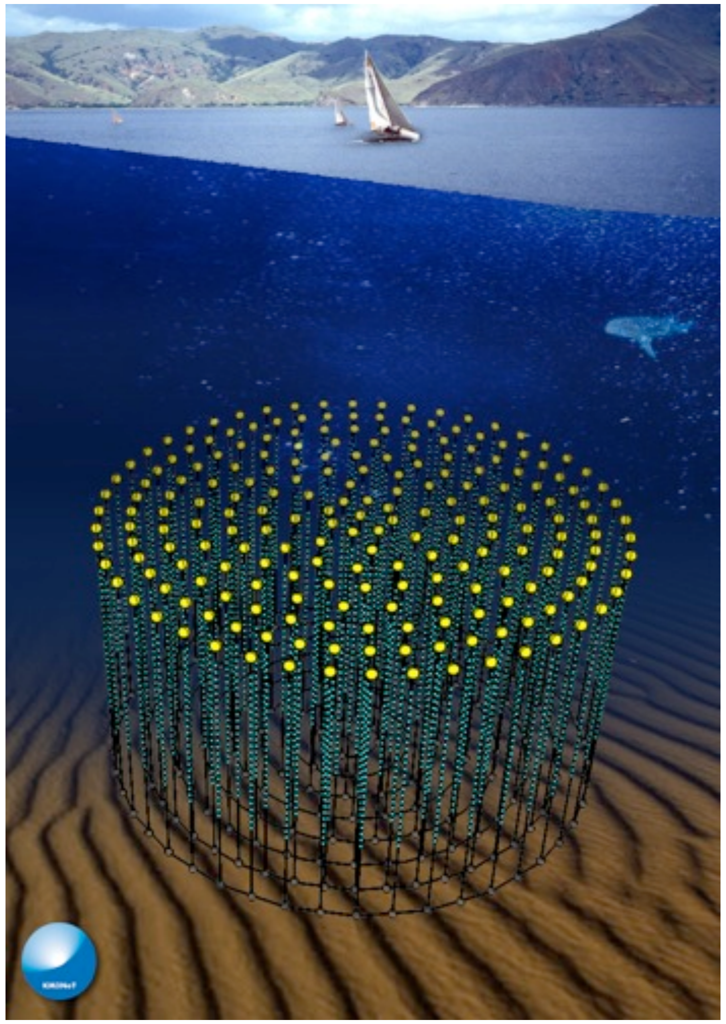
Expected performance:

- Muons (E>10 TeV):
  - A_{eff} ~ 0.2 – 0.5 km^2
  - $\delta\theta_{med}$~ 0.5°-1°

V. Aynutdinov (VLVnT 2009)

KM3NeT

- Future cubic-kilometre scale neutrino telescope in the Mediterranean Sea (joint effort of ANTARES, NEMO, NESTOR)
- Exceeds Northern-hemisphere telescopes by factor ~50 in sensitivity
- Exceeds IceCube sensitivity by substantial factor
- Focus of scientific interest: Neutrino astronomy in the 1 to 100 TeV range
- Provides node for earth and marine sciences



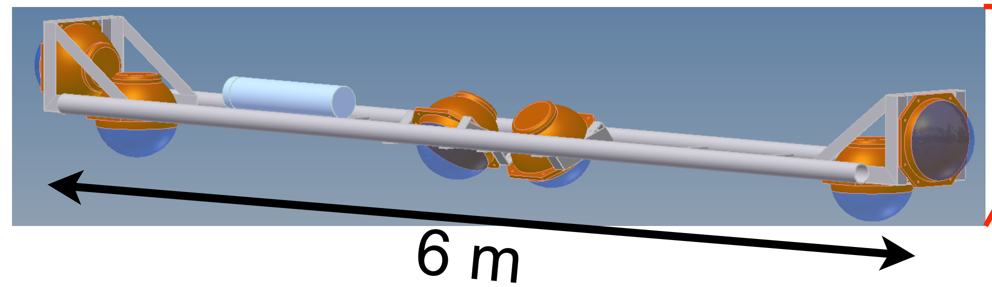
Artist's view

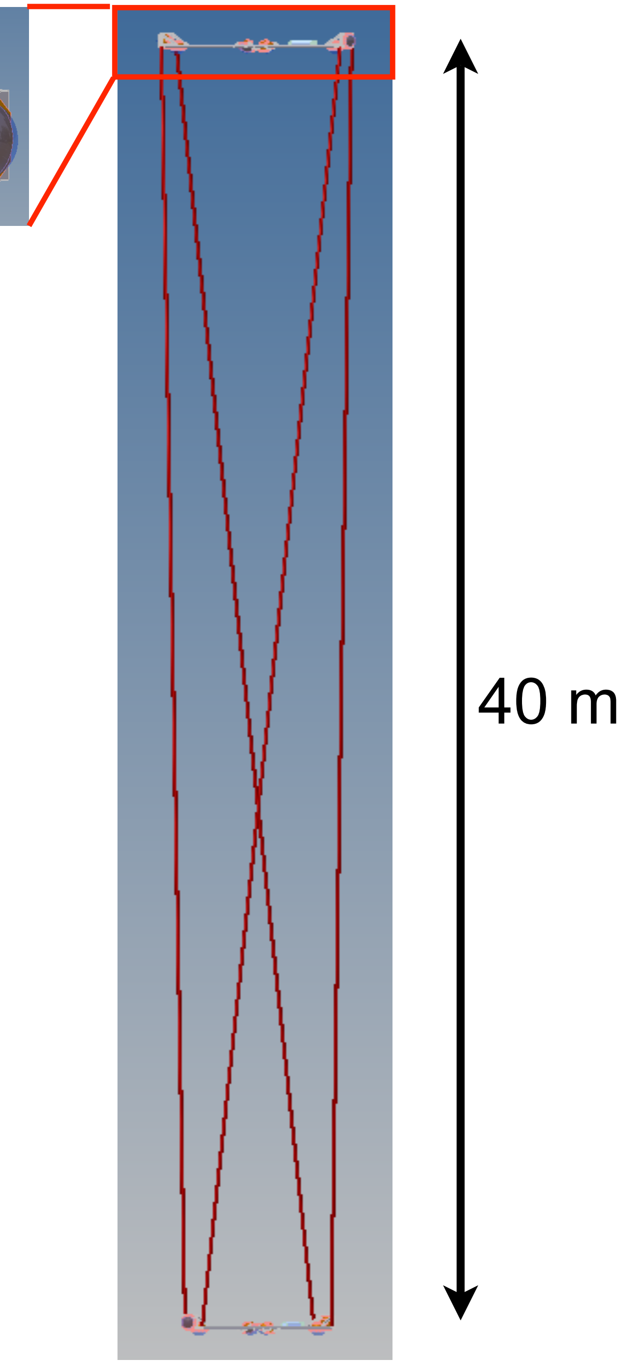
EU-funded Design Study 2006 – 2009
Supported by ESFRI, ASPERA, ASTRONET

KM3NeT: the Challenges

- Technical design
  - Mechanical structures, backbone cable
  - Optical Modules
  - Front-end electronics
  - Readout, data acquisition, data transport
  - Sea-bed network: cables, junction boxes
  - Calibration devices
  - Deployment procedures
  - Shore infrastructure
  - Assembly, transport, logistics
  - Risk analysis and quality control
- Simulation
  - Determine detector sensitivity
  - Optimize detector parameters
- Site characterization
- Earth and marine science node

Flexible tower with horizontal bars





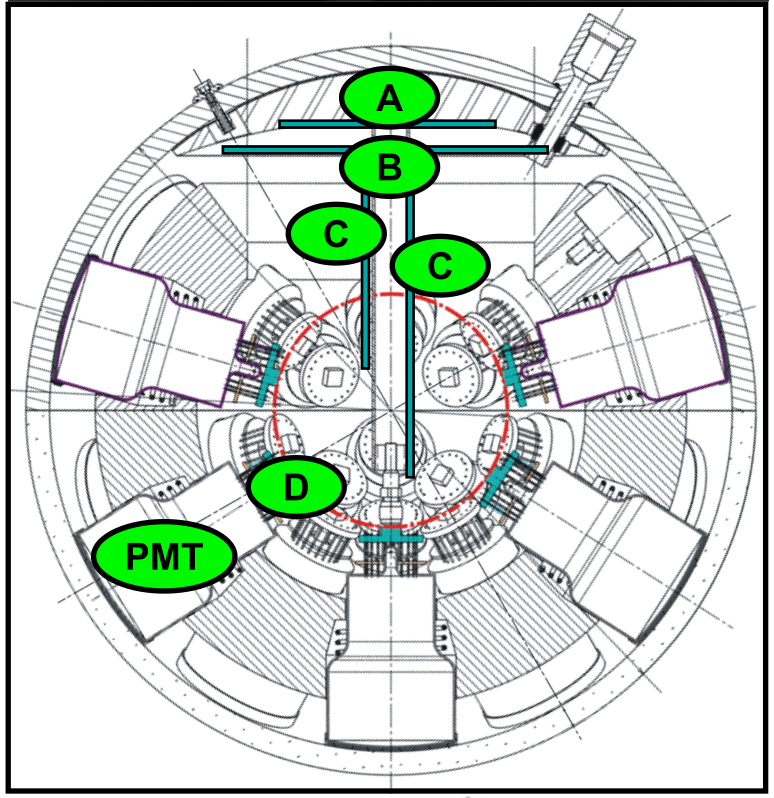
Semi-rigid system of horizontal elements (storeys):

- 20 storeys
- Each storey supports 6 OMs in groups of 2
- Storeys interlinked by tensioning ropes, subsequent storeys orthogonal to each other
- Power and data cables separated from ropes

U. Katz (VLVnT 2009)

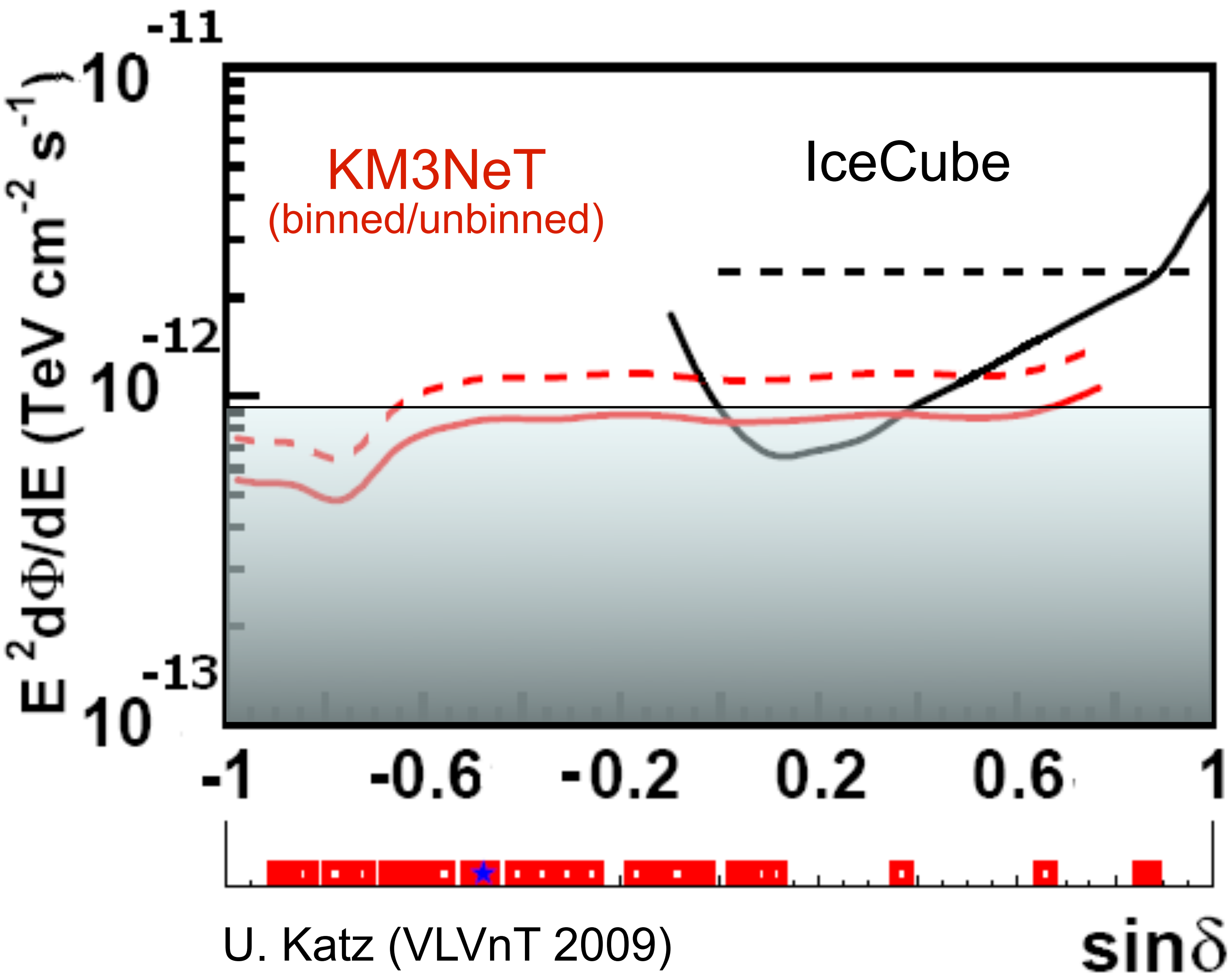
OM with many small PMTs

- 31 3-inch PMTs in 17-inch glass sphere (cathode area ~3x10” PMTs)
  - 19 in lower, 12 in upper hemisphere
  - Suspended by compressible foam core
- 31 PMT bases **(D)** (total ~140 mW)
- Front-end electronics **(B,C)**
- Al cooling shield and stem **(A)**
- Single penetrator
- 2mm optical gel (ANTARES-type)



U. Katz (VLVnT 2009)

Point source sensitivity (3 years)



Aharens et al. Astr. Phys. (2004) – binned method

R. Abbasi et al. Astro-ph (2009) scaled – unbinned method

Average value of sensitivity from R. Abbasi et al. Astro-ph (2009)

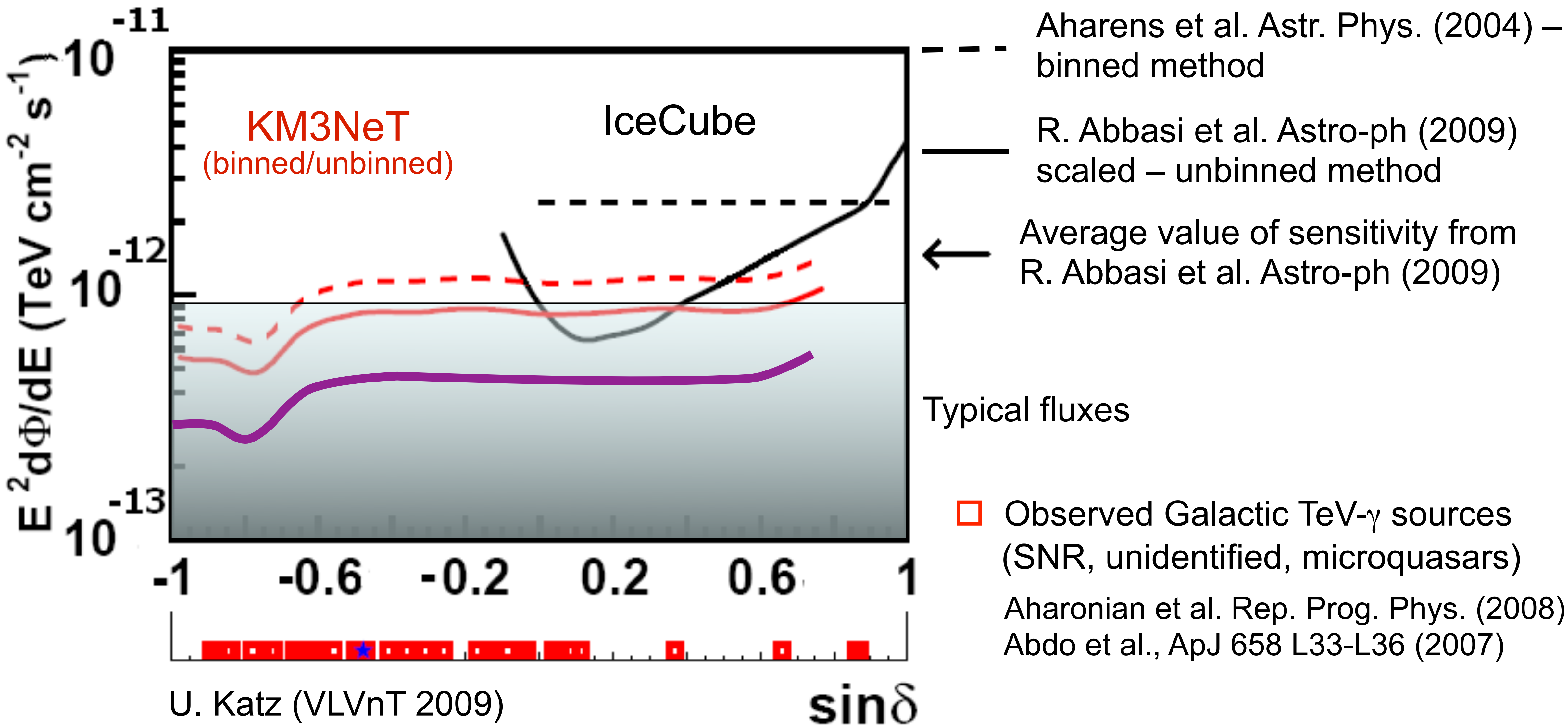
Typical fluxes

Observed Galactic TeV-γ sources (SNR, unidentified, microquasars)

Aharonian et al. Rep. Prog. Phys. (2008), Abdo et al., ApJ 658 L33-L36 (2007)

Estimated costs: ~100 MEuro (+10% man power)

Point source sensitivity (3 years)



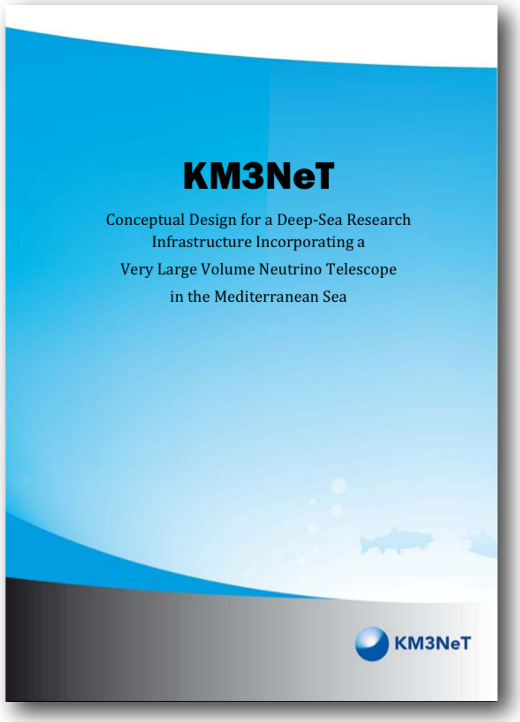
Estimated costs: ~100 MEuro (+10% man power)

Note: Doubled sensitivity for about double price . . .

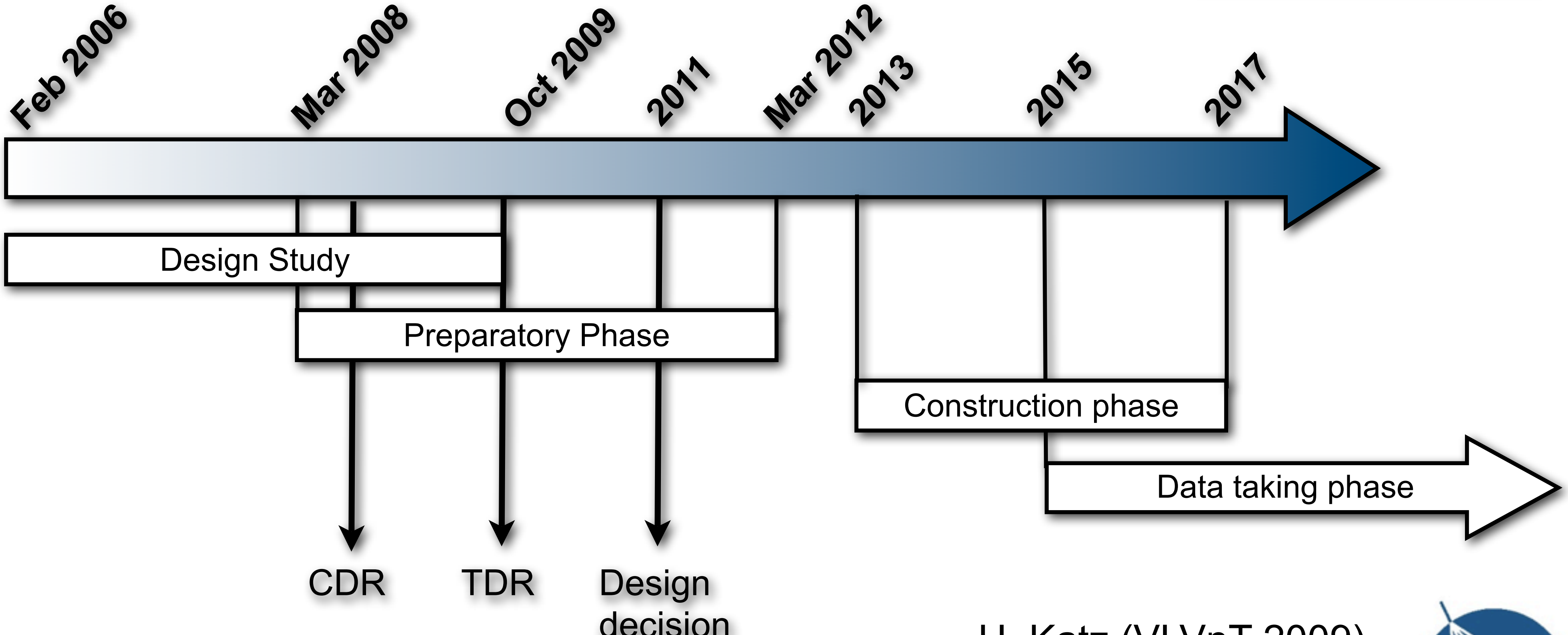
Next steps and timeline

Next steps: Prototyping and design decisions

- organized in Preparatory Phase framework
- final decisions require site selection
- expected to be achieved in ~18 months



Timeline:



U. Katz (VLVnT 2009)

Summary

- Neutrinos provide complimentary information to gamma-rays and protons of the high-energy universe
- So far no cosmic high-energy neutrinos identified
  - IceCube enters region with realistic discovery potential
  - Significantly more sensitive detector in the North needed to further advance into discovery region and cover full sky

    KM3NeT currently in design phase

The real voyage of discovery consists
not in seeking new landscapes,
but in having new eyes . . .
Marcel Proust

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Marie Curie Actions
Human Resources and Mobility Activity

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